NISTIR 4811

ORNL/Sub/83-21322/01

Abrasive Wear By Coal-Fueled Diesel Engine and Related Particles

L. K. Ives

Prepared for:
Oak Ridge National Laboratory
Oak Ridge, TN 37831

Managed by:
Martin Marietta Energy Systems, Inc.
for the
U.S. Department of Energy
Under contract No.
DE-AC05-840R21400

Report prepared by:

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Materials Science and Engineering
Laboratory
Ceramics Division
Gaithersburg, MD 20899

Contract Number DE-A105-830R21322

NIST

NISTIR 4811

ORNL/Sub/83-21322/01

Abrasive Wear By Coal-Fueled Diesel Engine and Related Particles

L. K. Ives

Prepared for:
Oak Ridge National Laboratory
Oak Ridge, TN 37831

Managed by:
Martin Marietta Energy Systems, Inc.
for the
U.S. Department of Energy
Under contract No.
DE-AC05-84OR21400

Report prepared by:
U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Materials Science and Engineering
Laboratory
Ceramics Division
Gaithersburg, MD 20899
Contract Number DE-A105-83OR21322

September 1992

U.S. DEPARTMENT OF COMMERCE
Barbara Hackman Franklin, Secretary

TECHNOLOGY ADMINISTRATION
Robert M. White, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
John W. Lyons, Director

"Research sponsored by the U.S. Department of Energy, AR&TD Fossil Energy Materials Program, DOE/FE AA 15 10 10 0, Work Breakdown Structure Element NIST-3"

ABSTRACT

The development of commercially viable diesel engines that operate directly on pulverized coal-fuels will require solution to the problem of severe abrasive wear. The purpose of the work described in this report was to investigate the nature of the abrasive wear problem. Analytical studies were carried out to determine the characteristics of the coal-fuel and associated combustion particles responsible for abrasion. Laboratory pin-on-disk wear tests were conducted on oil-particle mixtures to determine the relationship between wear rate and a number of different particle characteristics, contact parameters, specimen materials properties, and other relevant variables.

TABLE OF CONTENTS

	Page
ABSTRACT	
TABLE OF CONTENTS	
1. INTRODUCTION	1
2. EXPERIMENTAL PROCEDURE	2
2.1 Wear Test Method	2
2.2 Particle Analysis Procedures	7
3. PARTICULATE MATERIALS	7
3.1 Coal-Fuel	8
3.2 Extracted Mineral Matter	13
3.3 Combustor and Engine Particles	14
3.4 Noncoal-Derived Particles	20
4. RESULTS AND DISCUSSION	20
4.1 Wear by Combustor Particles	20
4.2 Particle Concentration Effects	28
4.3 Effects of Particle Size and Hardness	34
4.4 Other Effects	37
4.4.1 Relative Humidity	37
4.4.2 Additives	39
4.4.3 Embedment	40
4.5 Wear of Selected Materials	42
4.6 Wear of WC-6Co	47
5. SUMMARY	51
6. RECOMMENDATIONS	53
7. ACKNOWLEDGEMENTS	54
8. REFERENCES	54
Distribution	59

1. INTRODUCTION

During the period beginning about a decade after the invention of the diesel engine in 1892 and extending into World War II, a considerable effort was mounted in Germany to develop diesel engines capable of operating on dry powdered coal. Piston ring and cylinder liner wear rates as much as 500 times greater than experienced with petroleum derived diesel oil fuel were encountered.[1] This was a serious, if not limiting, impediment to the development of successful coal-fueled engines. Recent efforts in this country, which have focussed primarily on the use of low ash content (0.5 - 1.5wt.%, dry basis) coal/water slurry fuels, have also experienced extremely high engine component wear rates. For example, utilizing a diesel engine converted for direct operation on coal/water slurry fuel, Nydick, Porchet and Steiger[2] measured piston ring wear rates ranging from 56 to 161 times greater than those normally observed with #2 diesel oil-fuel (DF2). The corresponding cylinder liner wear rates were also much higher——namely, 13 to 42 times greater than with DF2. Comparably high wear rates have been observed by others including General Electric Corp.[3], engaged in the development of a coal-fueled diesel locomotive engine, and A. D. Little, Inc. (in conjunction with Cooper-Bessemer) [4] in their effort to develop large, stationary coal-fueled engines. The piston ring and cylinder liner materials in the above examples were the conventional ones designed for DF2 operation. They ranged from relatively soft grey cast iron to much harder chromium plating.

Development of commercially viable coal-fueled diesel engines will require piston ring and cylinder liner wear lives comparable to those achieved with current DF2 engines. It is clear that this cannot be attained with the conventional engine materials. Materials of significantly greater wear resistance and perhaps new piston ring designs will be required. Recognizing this need, both General Electric Corp.[3] and A. D. Little, Co.[5] have recently explored the use of more wear resistant materials. Among the most promising have been tungsten carbide-cobalt composites——materials that are traditionally used when a condition of severe abrasive wear is encountered. Short term engine tests have indicated that rings and liners employing these materials deliver substantially improved wear lives but still fall short of the desired goal.[3,5]

The purpose of the work reported here has been to address the problem of high piston ring and cylinder liner wear rates, mainly from the point of view of identifying the critical variables controlling wear and obtaining an understanding of the basic wear processes involved. A two-fold approach was taken. First, the nature of the coal-fuel related particles responsible for the high wear rates was investigated. Clearly, information on the nature of the abrading particles could be used to assist in the selection of the most suitable ring and liner materials, and perhaps in the formulation of more effective lubricants. Also, efforts to develop improved ring designs could benefit.

Second, laboratory wear tests were carried out to determine the relative effect on wear rate of various coal-fuel related particles, including the unburned coal-fuel, mineral matter particles extracted from coal, and particles associated with the combustion of coal-fuel. Additional tests were carried out using well-characterized particles of several different types to determine the effect of such important parameters as particle hardness and size. Also, recognizing that the ring and liner wear problem will be solved largely through the application of wear resistant materials, experiments were conducted to determine effect of materials properties on wear rate. The materials studied included pure metals, alloys, glasses, cermets and ceramics. Most of the results presented here can be found in a series of semiannual reports[6-11] and in reference[12]. Finally, it should be pointed out that this problem—the high rate of ring and liner wear in coal-fueled diesel engines—has and continues to be addressed by GE[3], A. D. Little, Inc. - Cooper-Bessemer[5], Southwest Research Institute[13], and Adiabatics, Inc.[14].

2. EXPERIMENTAL PROCEDURE

2.1 Wear Test Method

Laboratory wear test methods vary widely with respect to the degree to which they simulate the tribological conditions experienced by the actual components in a service environment. Some methods attempt to provide a close simulation of the conditions, perhaps using the components themselves. Other methods are generic in design and are used to rank the performance of different materials and lubricants, or to study particular wear modes and mechanisms. Often, the more closely the test method simulates the component conditions, the more complex and expensive it is to set up and conduct. Generic methods are favored by their simplicity, relatively low cost, and the capacity to maintain precise control over operating conditions.

In these experiments, a modification of the widely used, generic, pin-on-disk test method was employed. With the conventional pin-on-disk configuration, for example as is described by ASTM Standard Test Method G99-90 [15], a stationary pin is pressed against a rotating disk at some distance from the center of rotation; alternatively, the disk may be held stationary with the pin functioning as the moving element. In either case, the pin traverses a circular path on the disk. The design used in this work differed from the standard arrangement in that both the pin and the disk were rotated. The configuration is shown schematically in Fig. 1. Both single-pin, Fig. 1a, and three-pin, Fig. 1b arrangements were used. With the three-pin arrangement wear data could be obtained under nearly identical conditions on three different pins of the same or different materials. As illustrated in Fig. 1, the pin and disk

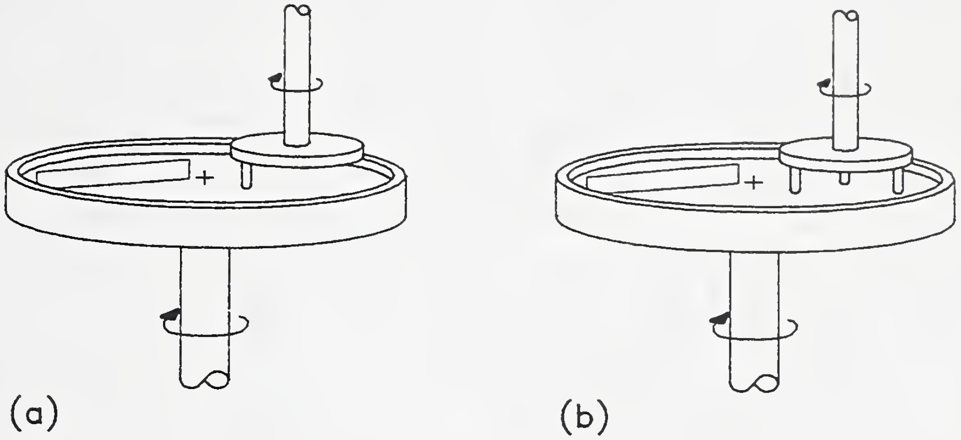


Fig. 1. Rotating pin-on-disk test configuration (a) single pin, (b) 3-pin.

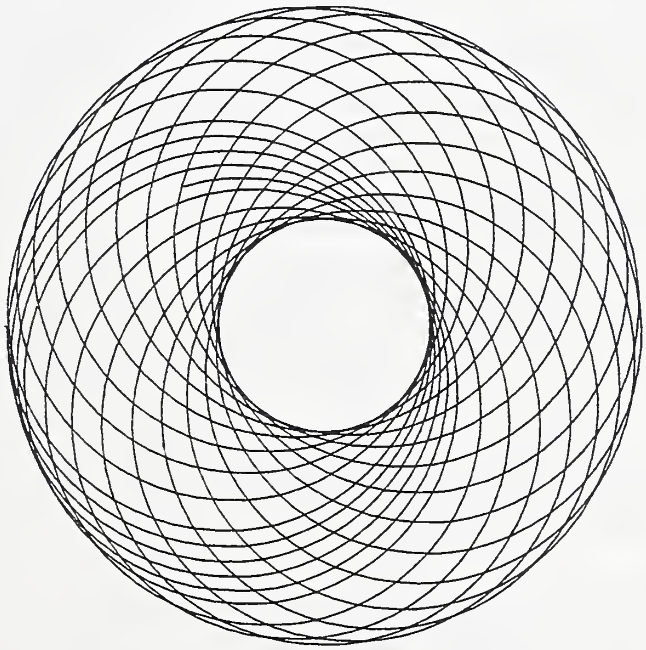


Fig. 2. Computed path traced out by pin on the disk surface.

specimen holders are attached to parallel but offset shafts. Rotation of the shafts is in the same direction but at slightly different speeds. Thus, the pin traces out a crisscrossing helical path about the center of rotation of the disk. Figure 2 is a computed plot of the path for a little more than one half of a cycle. The nature of the motion is such that the direction of sliding of the pin against the disk changes continuously throughout the cycle. With the conventional pin and disk design, sliding against the pin is unidirectional. Additional discussion of the rotating pin-on-disk method can be found in reference[16].

For the purpose of the present investigation of abrasion, the rotating pin-on-disk design has several advantages over the conventional arrangement. With the conventional design, the length of the wear track on the disk is relatively small. At high wear rates, a deep groove is rapidly worn into the disk. The result is a nonflat, more difficult to measure pin scar geometry. With the rotating pin-on-disk design the path is several times longer; this, together with the crisscrossing pattern, allows a much longer test interval without interruption for refinishing. An additional benefit of the rotating pin-on-disk design, particularly in connection with the present study, is the stirring action provided by the pin that assists in maintaining a well mixed and constant supply of lubricant to the sliding path.

There are also disadvantages associated with the rotating pin-on-disk design. Measurement of friction force is complicated by the fact that both the pin and the disk are in motion, and the moment of the force about both shafts changes continuously as a result of the configuration geometry. The present equipment was not instrumented for friction force measurement, although this capability has been incorporated into other designs.[17] Also, in general, it is not feasible to measure disk wear. This is because the wear loss is distributed over a relatively large area, and, except under the most severe conditions, the depth of the track is very small.

Finally, neither the rotating pin-on-disk design nor the conventional design simulates the motion described by the piston ring as it slides against the cylinder liner in an engine. As indicated above, with the rotating pin-on-disk design the direction of sliding on the pin changes continuously, and with the conventional design it remains constant and unidirectional. In contrast, the motion of the piston ring against the cylinder wall is predominately linear-reciprocating with a slight directional change due to the slow rotation of the ring in the piston groove.

An important consequence of the reciprocating motion of the piston ring and the varying load imposed by the cycling internal gas pressure, is a periodically varying lubricant film thickness at the ring-liner contact. It is generally accepted that a condition of hydrodynamic lubrication prevails at this contact except at the top and bottom reversal locations where boundary conditions exist. That is, over the path the ring traverses, a film is present that varies in thickness from perhaps several micrometers to essentially no thickness at the reversal locations. With particles present in the lubricant, only those particles that are larger than the film thickness will abrade the surface. Thus, even the smallest particles are potentially able to cause damage during reversal. Also, the varying contact spacing provides a means of trapping particles and enhancing abrasive wear. A similar condition of varying film thickness might have been realized by modifying the rotating pin-on-disk machine. The modification would consist of rotating the pin and disk in opposite directions or rotating them in the same direction at greatly different speeds. However, neither of these modifications was attempted.

Unless otherwise specified in the discussion, the majority of the tests in this investigation were conducted according to the conditions outlined in Table 1. As indicated in Table 1, two different disk materials were used: O-2 tool steel heat treated to a hardness of 730 Knoop(200g) and 52100 steel heat treated to a hardness of 810 Knoop(200g). However, most of the tests were conducted with 52100 steel disks. The results obtained with the two different disk materials were similar except under conditions where the wear rate was low. Low wear rates occurred when no particles were added to the oil or when abrasion associated with the added particles was small. Then, O-2 tool steel disks gave somewhat higher pin wear rates. This divergence was attributed to differences in carbide and inclusion content of the two steels.

Table 1. Wear Test Conditions

Disk material -- O-2 tool steel (730 HK_{200g})
52100 steel (810 HK_{200g})

Pin material -- 52100 steel bearing ball (820 Knoop)

Load per pin -- 15 N

Speed -- 63-64 cm/s

Atmosphere -- Air, 20 - 65% relative humidity

Temperature -- 23±2 C

Oil -- Paraffinic mineral oil (335-365 SUS @ 37.8 C)

Oil+Particle charge per test -- 2 ml

Most of the experiments that were designed to study the effects of such variables as particle size, type, and concentration utilized 52100 steel pins. These pins were standard grade 25, 3/8 inch diameter bearing balls. Bearing balls provide a test specimen that is extremely precise in dimensions, highly consistent with respect to finish and metallurgical properties, and that are quite low in cost. By repositioning, ten or more independent tests could be carried out on the same ball. Other pin materials that were studied in addition to 52100 steel are listed in Table 6 of the Results and Discussion section. Although some of the listed materials were available in the form of bearing balls, others were not. In the latter case, pins with a conical tip, illustrated in Fig. 3, were prepared. When conical pins were used, a flat was always preworn on the pin before initiation of the test. Flats were also preworn on balls for some tests to avoid the initial period of high contact stress. For both conical and ball geometries, wear volume determinations were based on measurement of the scar diameter.

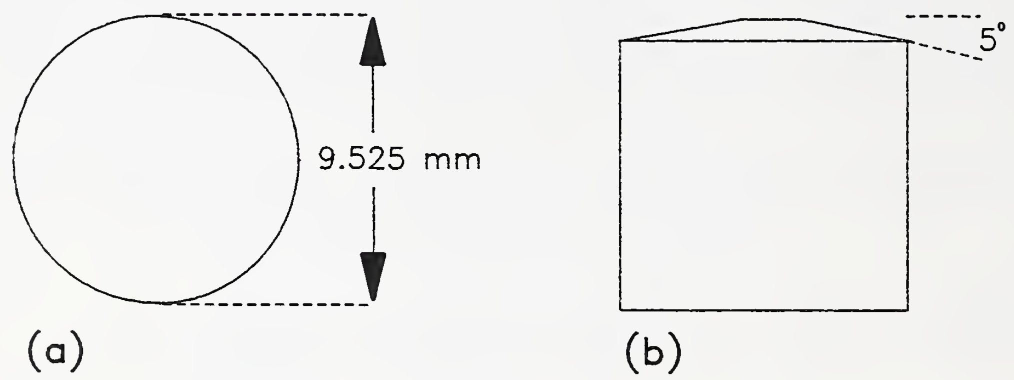


Fig. 3. Drawing of spherical (a) and conical pins (b).

For most of the tests employing 52100 steel pins, a distance of 833 m (5000 revolutions of the disk) was used to determine wear rate. For materials having higher wear resistances than 52100 steel, such as sintered tungsten carbide, much greater sliding distances were required. As indicated in Table 1, the wear tests were carried out in air with a relative humidity that ranged from a low value of less than 20% to as high as 65%. Although the relative humidity was not controlled it was measured for each test.

In general, the procedure followed in evaluating the effect of particle additions was first to conduct a test without particles added to the oil. In this way a baseline or reference value for wear was established. The "pretest" procedure also served to indicate the condition of the disk. A large deviation in wear rate from the established baseline value signalled that the condition of the disk surface had probably been altered by a previous test and that refinishing was required.

2.2 Particle Analysis Procedures

Several methods were used to characterize the various particulate materials. One or more samples of each material were examined in the SEM to determine particle morphology. Analysis of particle composition was carried out by means of an x-ray energy dispersive spectrometer (EDS) system attached to the SEM. Thermogravimetric (TGA) analyses were carried out on two of the particulate materials (combustor and filter residue, see below) to determine the mass fractions of coal, mineral matter, and volatile constituents present.

Measurement of particle size distributions, when not available from the supplier, was obtained by means of a Horiba LA-500 Analyzer. This instrument utilizes laser light scattering for size determination. The analysis is based on Fraunhofer diffraction and Mie scattering theories. The applicable particle size range for the instrument is 0.1μm - 200μm. Particulate materials of interest in this study were fairly well covered by this range, although according to SEM examinations there was usually a small weight fraction of particles less than 0.1μm in size. However, since wear rate was found to decrease exponentially with decreasing particle size, the contribution of these particles was probably quite small.

3. PARTICULATE MATERIALS

A list of the particulate materials studied, together with size and hardness information, is given in Table 2. Most important with respect to this investigation are the two materials associated with the combustion of coal-fuel; namely, the combustor particles and the engine-filter residue particles. These are likely to be most nearly representative of the particles to which the piston rings and cylinder liners are exposed. Also of direct interest with respect to diesel engine wear are the unburned coal-fuel particles and the mineral matter particles separated from coal during processing. Both types of particles will be present on the cylinder wall surfaces of an operating coal-fueled engine. By evaluating them independently their separate contributions to wear can be determined. The other particles in Table 2 were employed to establish the influence on wear rate of specific particle characteristics such as hardness and size.

A brief description of each of the particulate materials is given in the following sections.

Table 2. Particulate Materials Used in Wear Tests

MATERIAL	SIZE (μm)	HARDNESS (kg/mm^2)
Otisca Blue Gem Coal-fuel	4	34
Mineral Matter Extracted from Coal	1	1000 max.
GE Combustor Particles	5	1000 max.
Diesel Engine Filter Residue	3	1000 max.
GE Aluminum Oxide	2	2100
Aluminum Oxide	1	2100
Aluminum Oxide	3	2100
Magnesium Oxide	2	700
Min-U-Sil (R)5 (quartz)	2	1000 max.
Quartz BCR #66	1	800-1000
Quartz BCR #70	3	800-1000
Quartz BCR #67	10	800-1000
Diamond	1	10,000

3.1 Coal-Fuel

The coal-fuel used in this investigation was a product of Otisca Industries. It was prepared from Kentucky Blue Gem coal, a low-ash-content, eastern bituminous coal. Utilizing a physical beneficiation method Otisca Industries refers to as the T-process[18], the ash content of the raw coal (on a dry basis) was reduced from about 2% to less than 1%. Grinding to a small particle size, nominally 5μm, is a key element in the cleaning procedure since this is the means by which mineral matter is freed from the coal. Once released, the mineral matter and coal are separated by a selective fluid agglomeration process. Typical properties of Otisca Blue Gem coal-fuel are given in Table 3.

Streeter[19] conducted x-ray diffraction studies to determine the nature of the mineral matter content of both Kentucky Blue Gem feed coal and the coal-fuel prepared by Otisca Industries. The results are summarized in Table 4. The analysis utilized low temperature ash to minimize the oxidation and transformation of the mineral species. It may be noted that less than one half of the total mass of the ash is accounted for in Table 4. Streeter suggests that the remaining material consisted of amorphous constituents, unidentified crystalline species, crystalline species at a concentration too low to be detected, and residual carbonaceous material that was not burned in the ashing process. It is important to note that the mineral species identified in Kentucky Blue Gem coal are typical of minerals found in other types of coal mined in the USA.[20]

Table 3. Properties of Otisca Kentucky Blue Gem Coal-Fuel

49% Solids Content Coal/Water Slurry	<u>Ash Analysis</u>
	29.13% Silica
	25.86% Alumina
<u>Proximate Analysis (Dry Basis)</u>	3.18% Titania
0.88% Ash	25.09% Ferric Oxide
39.12% Volatile Matter	4.94% Lime
60.00% Fixed Carbon	1.39% Magnesia
14,123 Btu/lb.	1.73% Potassium Oxide
0.79% Sulfur	1.44% Sodium Oxide
	3.58% Sulfur Trioxide
<u>Ultimate Analysis (Dry Basis)</u>	0.39% Phosphorous Pentoxide
80.34% Carbon	0.46% Strontium Oxide
5.13% Hydrogen	0.37% Barium Oxide
1.92% Nitrogen	0.02% Manganese Oxide
0.15% Chlorine	2.42% Undetermined
0.79% Sulfur	
0.88% Ash	
10.79% Oxygen (by difference)	

Typical hardness values for the minerals identified by Streeter are given in Table 5. Quartz is the hardest mineral present, followed by pyrite. The hardness of the unidentified amorphous constituents is not known; however, if they are silicates their hardness is not likely to exceed that of quartz. An amorphous phase is usually softer than its allotropic crystalline phase.

The selection of materials to resist abrasive wear, in general, is based on the hardest particle-type present at greater than trace concentrations. For Kentucky Blue Gem and, as noted above, for most other types of coal, this is quartz. Trace amounts of harder species such as Al_2O_3 may be present but at concentrations too small to be important. Thus, if a material exhibits adequate abrasive wear resistance in the presence of

Table 4. Mineral Concentrations in Otisca Blue Gem Low-Temperature Ash and Coal Samples[19]

	Weight Percent of Mineral in Low-Temperature Ash		Mineral Content on Dry Coal Basis (Wt.%)*	
Mineral	Raw Coal	Product Coal	Raw Coal	Product Coal
α-Quartz	1.7	0.9	0.040	0.009
Kaolinite	12.2	12.3	0.288	0.[illegible]9
Anhydrite	1.4	5.9	0.033	0.057
Calcite	3.3	1.2	0.078	0.012
Pyrite	19.8	1.1	0.467	0.011
Ferric Sulfate	9.5	13.1	0.224	0.127
Total:	47.9	34.5		

*Calculated from low-temperature ash content of coal

quartz particles, it should be satisfactory with respect to other, softer minerals. It is seen in Table 4 that the beneficiation process applied by Otisca Industries to Kentucky Blue Gem coal resulted in an appreciable decrease in the concentration of quartz and pyrite. This certainly will be of significant benefit with respect to minimizing the abrasivity of the product coal-fuel.

Scanning electron micrographs of Otisca coal-fuel particles are shown in Fig. 4. The particles are seen to have a blocky shape. Typical EDS spectra obtained from individual particles are shown in Fig. 5. The large copper peaks in the spectra arise from the copper surface on which the particles are dispersed. Copper was chosen as a substrate material because it is only present in the coal-fuel particles in trace amounts[19], and its peaks are well separated from the peaks of the elements that are of major interest. The spectrum in Fig. 5a indicates the presence of sulfur and oxygen in addition to carbon. (The carbon peak is comparatively small because of the relatively low sensitivity of the x-ray detector for this element.) Sulfur may be bound organically in the coal, or it may be a component of one or more of the mineral constituents that happen to be trapped in

Table 5. Hardness of Mineral Species in Kentucky Blue Gem Coal

Mineral	Hardness (mohs)
α-Quartz	7
Kaolinite	2-2.5
Anhydrite	3.5
Calcite	3
Pyrite	6-6.5
Ferric Sulfate	2.5

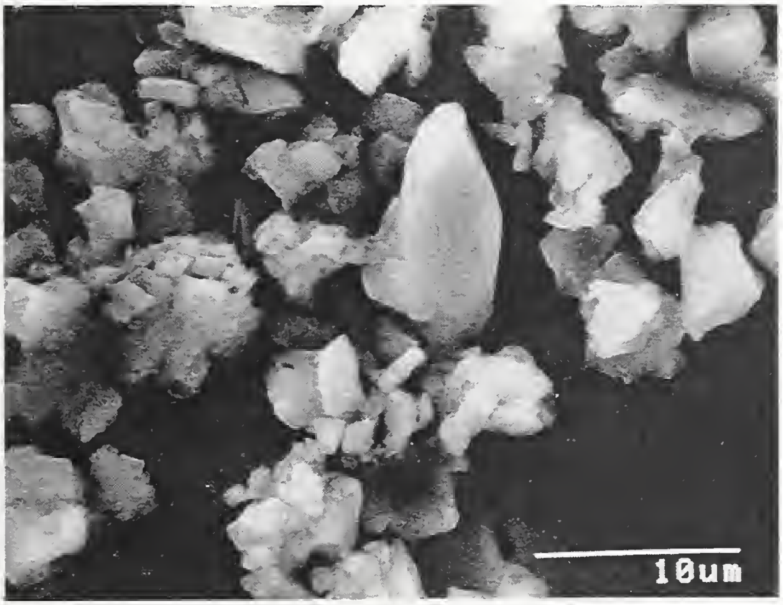
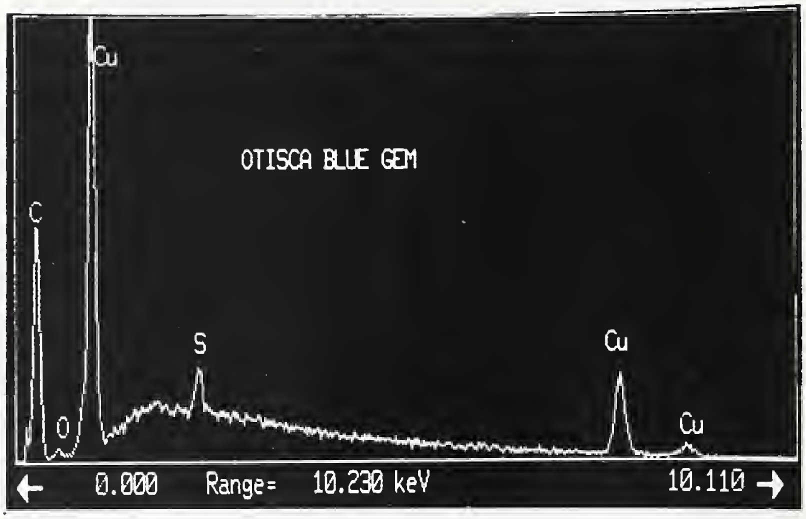


Fig. 4. SEM micrograph of Otisca Blue Gem coal-fuel particles.

(a)



(b)

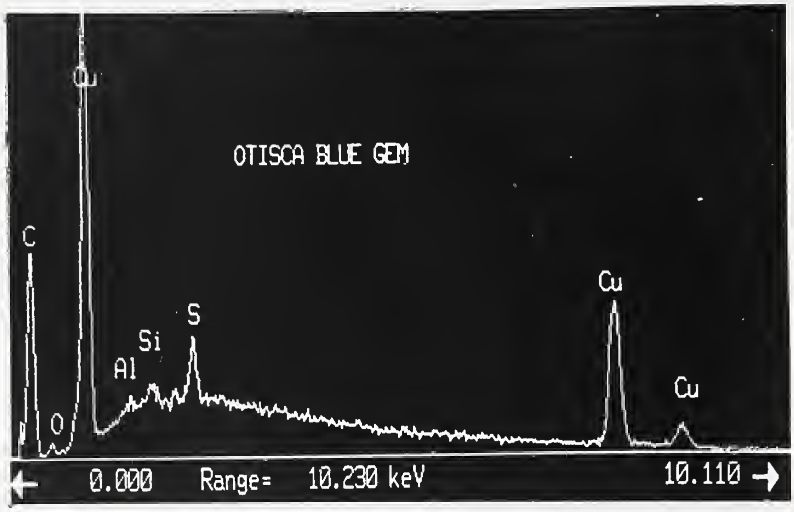


Fig. 5. Typical EDS spectra obtained from coal-fuel particles (a) Particle without detectable mineral related elements other than sulfur. (b) Particle containing mineral related elements. Copper peaks are from support.

the coal particle. The absence of other mineral-related element peaks in this spectra suggests that the sulfur may not be associated with a mineral constituent. Additives which are introduced into the coal-fuel slurry to control settling and agglomeration are an additional source of sulfur. Residue from the additives can remain on the particles after drying. There are several possible sources for the observed oxygen peak: water contained in the particle, oxidation of the coal, oxygen in additive residue on the coal, and copper oxide on the substrate.

The spectrum in Fig. 5b is similar to 5a but additional peaks associated with Al and Si are present. These elements are probably associated with mineral matter contained within the particle.

Although a number of particle collections such as that shown in Fig. 4 were examined, examples of isolated mineral particles were not found. This is not entirely surprising. Even if the entire mineral content contained in the coal-fuel was concentrated in independent mineral particles, at an average concentration of less than 1%, fewer than one in one hundred of the coal-fuel particles would be mineral. Since EDS spectra indicate that a considerable fraction of the mineral matter is incorporated in coal particles, the fraction of isolated mineral particles must be far less than one in one hundred. This finding is in agreement with results obtained by Keller [21] in his evaluation of the Otisca beneficiation process. He found that the process removed free mineral particles quite efficiently and that most of the remaining mineral material was still bound in the coal.

From the fact that much of the residual mineral matter is bound to coal particles, one may also conclude that the mineral matter particle size is smaller on average than the coal-fuel particle size. This is important with respect to wear, since wear rate, as will be described later, decreases with decreasing particle size.

3.2 Extracted Mineral Matter

An SEM micrograph of extracted mineral matter particles is shown in Fig. 6. The particles are more-or-less blocky in shape with sharp corners. It is expected that most of these particles have been exposed to crushing during grinding of the coal and may differ somewhat in abrasivity from particles still incorporated in the coal. In particular, the presence of sharp corners and edges produced by crushing can lead to increased abrasivity.

The distribution of mineral species present in the lot of mineral matter obtained for this investigation was not determined directly; however, an estimate can be obtained from Streeter's results presented in Table 4. Streeter determined the concentration of mineral species in raw coal and in product coal that had been processed by the Otisca method. The distribution of species present in extracted mineral matter can be determined

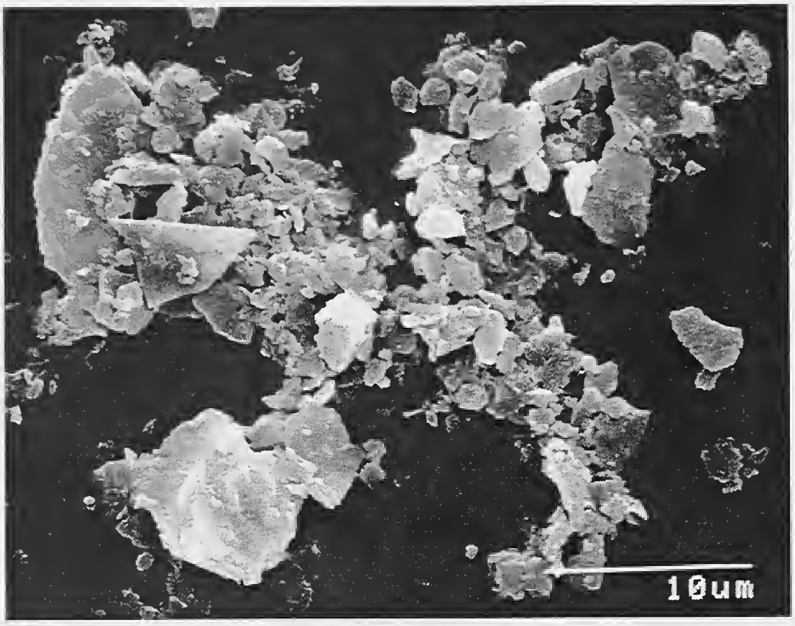


Fig. 6. SEM of mineral matter particles extracted during processing Blue Gem coal-fuel.

by comparing these two distributions. It is important to notice that the relative concentration of quartz particles in the product coal is less than in the raw coal so there must be a corresponding enhancement of quartz in the extracted matter. Because quartz is almost certainly more abrasive than the other mineral constituents identified, its increased concentration will render the extracted material more abrasive than the mineral matter remaining in the coal-fuel.

3.3 Combustor and Engine Particles

Two types of particulate materials derived from the combustion of coal-fuel were utilized in wear tests: turbine combustor particles and engine oil filter particles. Both were obtained from the General Electric Corporation. The combustor particles were collected during tests on an experimental gas turbine combustor. Shields, Spiro, and Koch[22] carried out a detailed examination of deposits generated during the combustor tests using x-ray diffraction and other analytical techniques. Since the deposits were formed by the accumulation of particles, both deposits and particles are expected to be closely related in composition and structure. Shields et al. determined that the deposits consisted of plagioclase and spinel structures, together with hematite, anhydrite, and noncrystalline material.

An SEM micrograph of a representative collection of combustor particles is shown in Fig. 7. In general, four different types of particles were observed. These were 1) unburned coal; 2) partially reacted coal, which is distinguished by the presence of porosity and often a higher mineral content than the unburned coal; 3) spherical fly-ash particles with no detectable carbon; and 4) soot particles similar to those produced during the combustion of diesel oil-fuel. An SEM micrograph of a porous particle is shown in Fig. 8a together with its associated x-ray spectrum in Fig. 8b. Similarly, a spherical particle and its x-ray spectrum are shown in Fig. 9a and 9b, respectively. Clusters of soot particles attached to the spherical particle can be seen in Fig. 9a. According to its x-ray spectrum, the porous particle in Fig. 8a contains, in addition to carbon, relatively large amounts of S and Fe, smaller amounts of O, Al, and Si, and trace amounts of Cl and Ca. The spherical particle in Fig. 9a contains relatively large concentrations of O, Al, Si, Ca, and Fe, together with smaller amounts of Mg and Ti. Carbon and sulfur were not detected, but the sensitivity of the thin window EDS detector to carbon was relatively low so that 10% or more carbon could have been present without response. It may be noted that many of the elements identified in the coal-ash analysis, Table 3, are present in this spherical particle.

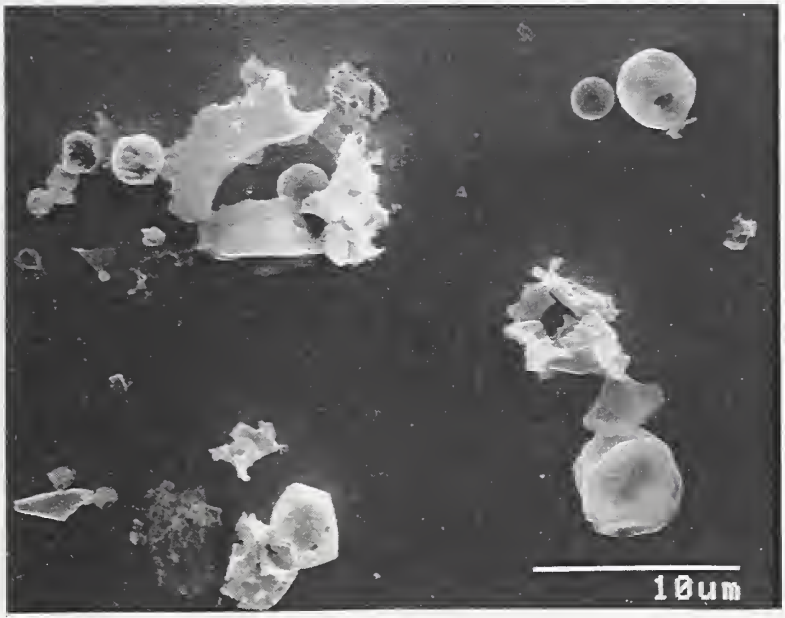
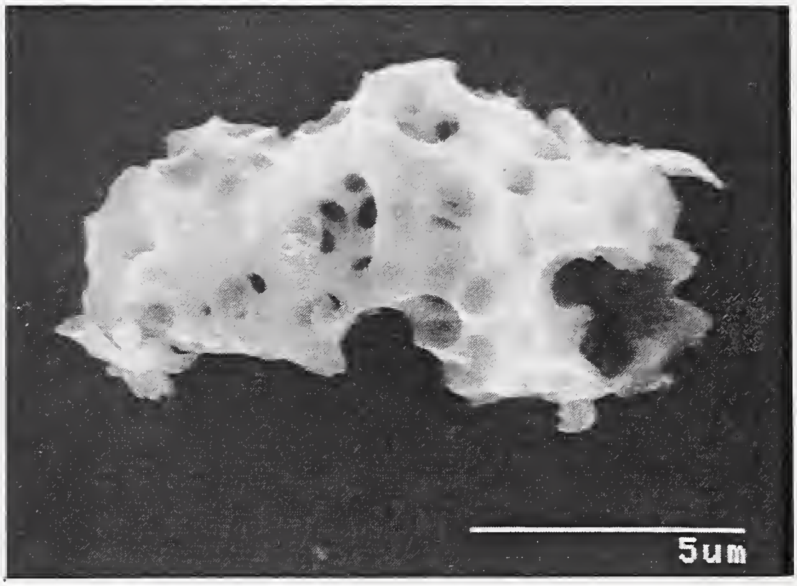


Fig. 7. SEM micrograph of combustor particles.

(a)



(b)

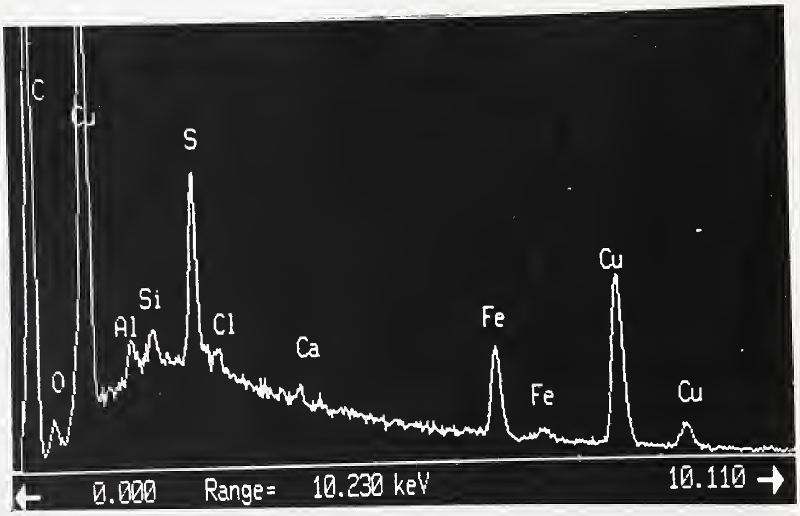
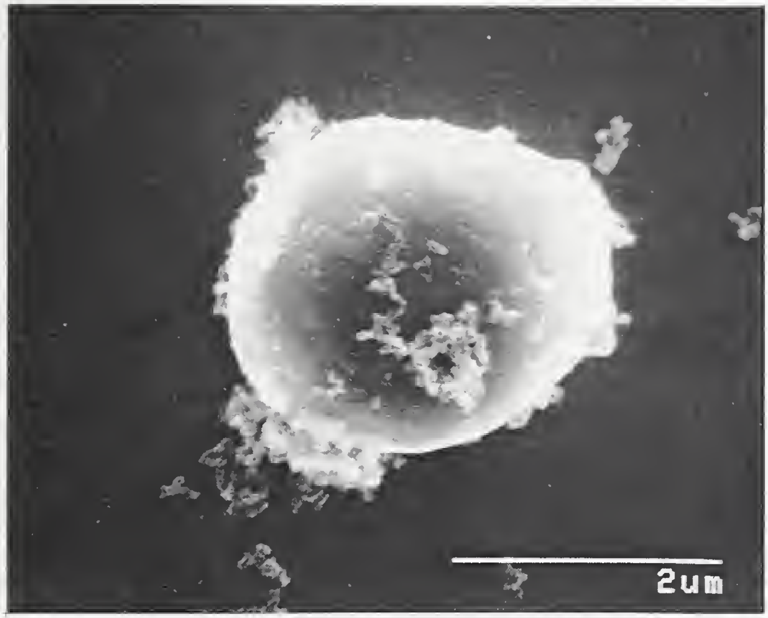


Fig. 8.(a) Porous combustor particle. (b) EDS spectrum from particle.

(a)



(b)

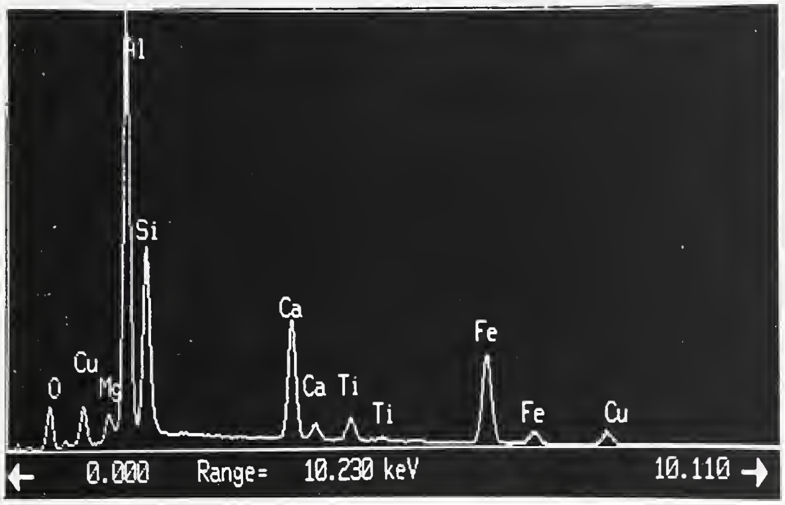


Fig. 9.(a) Spherical combustor particle. (b) EDS spectrum from particle.

Although combustion in both the turbine combustor and diesel engine takes place in a pressurized air environment, the conditions are not identical. Consequently, the resulting product particles may differ. The possibility of such differences was investigated on a qualitative basis utilizing SEM and EDS to compare the turbine combustor particles with particles collected from the exhaust of diesel engines operated on coal-fuel. (Comparison was also made with the engine filter particles described below which were obtained much later in this study.) The diesel exhaust particles for this comparison were obtained from General Electric Corporation and Adiabatics, Inc. The quantity of particles available was limited to a fraction of a gram—too little for use in wear tests. The GE exhaust particles were generated during operation of a conventional diesel engine that had been converted to run on coal-fuel. The Adiabatics particles were generated by an experimental low heat rejection engine.[23] The exhaust particles in both cases were found to be similar to each other and to the combustor particles. That is, unburned coal, partly reacted coal, spherical, and soot particles were observed. No attempt was made to determine if the fractional amounts of each particle type was similar; however, even when obtained from the same diesel engine there is likely to be considerable variation in distribution depending on the mode of operation, i.e., idle, full-load, etc.

Thermogravimetric analyses (TGA) were conducted on the combustor particles to obtain an indication of the amount of combustible matter, principally coal, present. The analysis was carried out in oxygen to a maximum temperature of 560°C. The results indicated that in excess of 65% was combustible.

Engine oil filter particles are likely to be closely representative of the particles that enter the ring-liner contact of an operating engine. The particles obtained from GE were contained in the accumulated residue taken from the centrifugal oil filter of an experimental diesel engine that had been operated on coal-fuel. The experimental engine was a section of an actual locomotive engine set up to evaluate engine components, the fuel injection system, and various engine operating characteristics in preparation for the development of a coal-fueled locomotive engine.[24] One cylinder of the experimental engine was operated on coal-fuel and a second cylinder on DF2.

The centrifugal oil filter served the entire engine. Thus, the accumulated residue contained particles generated from the combustion of DF2 as well as coal-fuel. Other debris associated with engine operation was of course present as well. It should be noted that even under coal-fuel operation, pilot injection of DF2 is employed to initiate combustion and soot resulting from DF2 will contribute to the accumulated particulate matter. It is also important to point out that the combustion conditions of this experimental engine often deviated considerably from those that would be expected in a fully operational coal-fueled diesel engine. Potentially, then, the particles accumulated in the oil filter also could be different, although it is expected that the greatest effect would be on the relative concentrations of the various types of particles rather than in the generation of new types of particles. In fact, as noted previously, SEM examination of the engine filter particles showed that they were similar to the combustor and diesel exhaust particles of quite different origin. Figure 10 shows an example of engine filter particles.

The filter residue was a mixture of engine lubricating oil and particles. At room temperature its consistency approached that of relatively stiff putty. The solid particle content was determined by washing the residue with hexanes over a 0.05 μm Nuclepore filter. Approximately 50% of the initial mass of the residue was retained on the filter. An SEM micrograph of retained particles is shown in Fig. 10. Both spherical ash particles and coal particles can be distinguished.

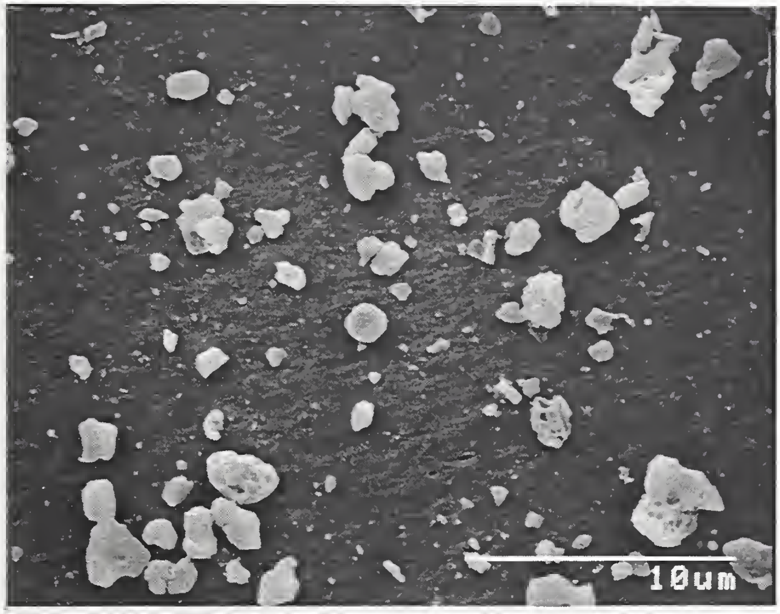


Fig. 10. Particles from centrifugal oil filter of engine operated on coal-fuel.

Thermogravimetric analyses to a temperature of 560°C were also conducted on the filter residue. Both argon and oxygen environments were employed. Analysis in argon provided a measure of the volatile mass fraction, in this case, primarily oil. The argon results indicated that about 65% of the residue was volatile. After exposure to oxygen about 13% of the mass remained, much of this was mineral matter and related ash.

3.4 Noncoal-Derived Particles

Quartz represents one of the hardest minerals commonly found in coal. Resistance to abrasion by quartz will therefore provide a useful measure of a materials suitability for piston ring and cylinder liner applications. For this reason quartz particles were employed in a number of experiments in this investigation. As indicated in Table 2, quartz particles from two different sources were used. The Commission of the European Communities Community Bureau of Reference quartz particles (designated BCR) are certified standard reference materials prepared for the purpose of calibrating particle size measurement instruments. Thus, they offered a valuable means of determining the effect of particle size on wear rate. Because of the high cost of the BCR quartz particles, however, their use was limited to a small number of selected experiments. Cost was not a constraint in the case of the Min-U-Sil(R)5 quartz particles that were available in large quantity. Except for the smaller average particle size, the distribution profile of the Min-U-Sil(R)5 particles was quite similar to that of the BCR #66 particles.

MgO, Al_2O_3, and diamond particles were employed mainly to study the effect of particle hardness on wear rate. These particles were metallographic polishing abrasives. Their size distributions were not measured. The sizes are those given by the supplier.

4. RESULTS AND DISCUSSION

The presentation and discussion of the experimental results which follows is organized into several sections. In the first section, attention is focussed on wear by combustor particles. A comparison is made between the effects of these particles and other coal related particles, namely, unburned coal-fuel particles and extracted mineral matter particles, which themselves are constituents of the combustor particles. Additional comparison is made to well characterized quartz, Al_2O_3, and MgO particles. This was done to gain insight into the relative abrasivity characteristics of the combustor particles and to demonstrate the importance of such parameters as particle hardness and size.

Following the first section, subsequent sections explore in more detail the effects of particle concentration, hardness, size, and other experimental variables. The final sections deal with the relative wear rates of different specimen materials.

4.1 Wear by Combustor Particles in Mineral Oil

Tests were carried out to determine the effects on wear rate of sliding distance and combustor particle concentration in mineral oil. Some tests were also conducted to determine the influence of relative humidity. Figure 11 shows the effect of

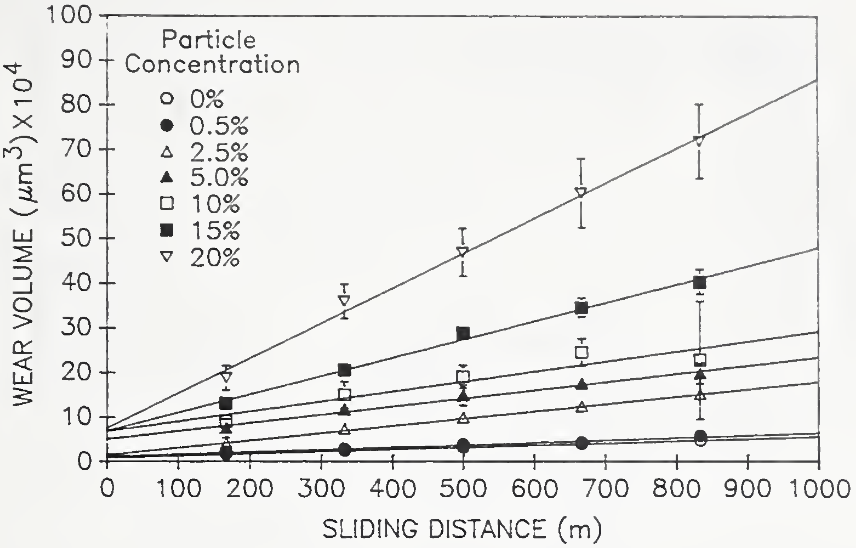


Fig. 11. Wear of 52100 steel pin as a function of sliding distance with different concentrations of combustor particles in mineral oil.

sliding distance on pin wear for several different concentrations of combustor particles. An O-2 tool steel disk was employed in these experiments, and the relative humidity was in the range 19 to 27%. The remaining test conditions are summarized in Table 1. Wear rate is seen to increase in a linear fashion at each concentration level. It may be noticed, however, that the linear regression curves fitted to the test data do not extrapolate to the origin but intersect the ordinate at positive values. This occurs because of a higher initial wear rate that is apparently due to the small contact area and accompanying high contact stress associated with the sphere-on-flat geometry. For distances greater than about 150 m the wear rate is seen to be nearly constant, depending only on concentration. Of course, the pin contact area increases as the amount of wear increases. Thus, except during the initial increment of sliding, the wear rate is nearly independent of contact area. As stated earlier, the reported wear rate values were determined for a sliding distance of 833 m, beginning with initial contact. Referring to Fig. 11, it is seen that including the initial increment of high wear rate results in a slightly higher average value than would be the case if the initial increment were rejected.

The influence of combustor particle concentration on wear rate is shown in Fig. 12. Values at each point were obtained from the same data used in plotting Fig. 11. Additional results are included in Fig. 12 at a higher, 60% relative humidity. Wear rate is seen not only to increase with increasing particle concentration but to increase more rapidly at high

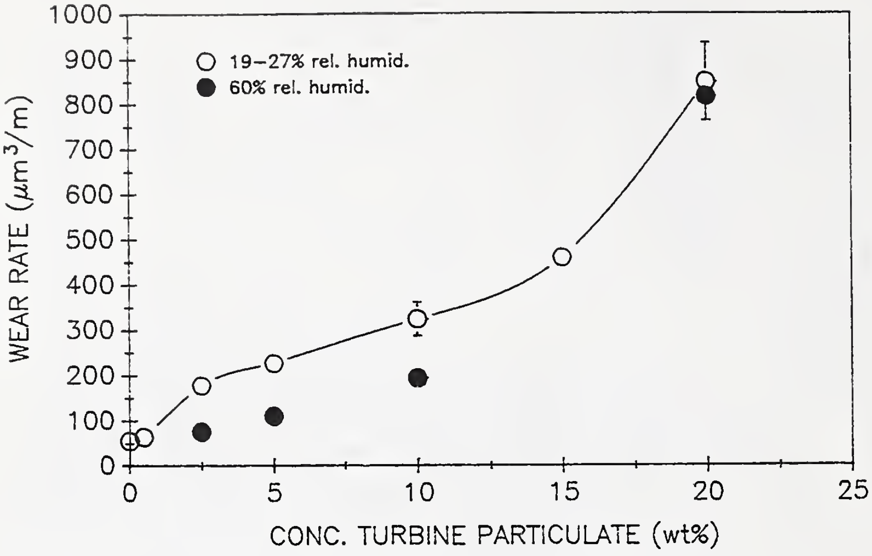


Fig. 12. Wear rate of 52100 steel pin as a function of combustor particle concentration in mineral oil at high and low relative humidities.

concentrations. This is true at both levels of relative humidity for which the data were obtained. Particle concentration, quite clearly, is a very important parameter. It can influence wear rate directly by determining the number of particles that enter the contact and also by affecting the rheology of the lubricant, which apparently explains the strong rise in wear rate at high concentrations. Additional results and discussion concerning the effects of particle concentration will be presented in a subsequent section.

As described earlier, the combustor particulate material consists of a mixture of unburned coal particles and combustion modified or synthesized particles. Tests conducted with unburned coal-fuel and extracted mineral matter particles give an indication of the contribution of these individual constituents to wear rate. The results are presented in Fig. 13. The corresponding base line result for oil without added particles is also shown. At a particle concentration of 10wt%, for which the data were obtained, the presence of unburned coal-fuel particles in the lubricating oil leads to a 65% increase in wear rate. The combustor particles produce a much greater, 6-fold increase and the extracted mineral matter particles cause a 30-fold increase. The observed changes in wear rate are, of course, a function of particle concentration and would be greater (or less) for larger (or smaller) concentrations. For example, according to Fig. 12 the combustor particles at a concentration of 20% cause a 20-fold increase.

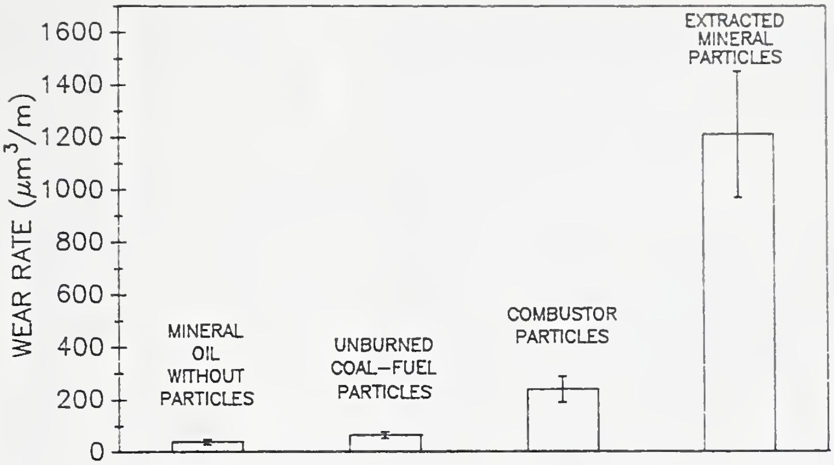


Fig. 13. Wear of 52100 steel pin lubricated with mineral oil and with mineral oil containing 10% of three different coal related particles.

Each of the particulate materials in Fig. 13 consists of a variety of constituent particle types. The differences in wear rate shown in Fig. 13 are related to the concentration, size, shape, and hardness of the constituents present. Thus, the extracted mineral matter material undoubtedly has the highest concentration of hard particles. The comparatively small wear rate associated with coal-fuel particles is consistent with its low concentration of hard particles. A significant fraction of the combustor particles consists of the relatively soft coal particles. Of the remaining particles, a major fraction are fly ash particles synthesized from mineral matter. These particles are spherical in shape, and spherical and rounded particles are usually found to be less abrasive than sharp, angular particles.

Even the 20-fold increase in wear rate obtained with 20wt.% combustion particles is significantly less than the 50-100 times increase reported by Nydick et al.[2] for piston ring wear in a diesel engine operating on coal-fuel. This probably reflects the fact that the gray cast iron ring material was much softer than the 52100 steel pin used in these experiments. Also, the conditions in an operating engine are quite different than those in this simple laboratory test. As discussed earlier, the reciprocating motion and varying load on the ring result in a fluctuating lubricant film thickness and this may allow more and larger particles to enter the contact.

In Fig. 14 the wear rate with combustor particles is compared to several other abrasives. Because of the large range in wear rates, values are plotted on a log scale. Quartz, as noted earlier, is of particular interest because it represents

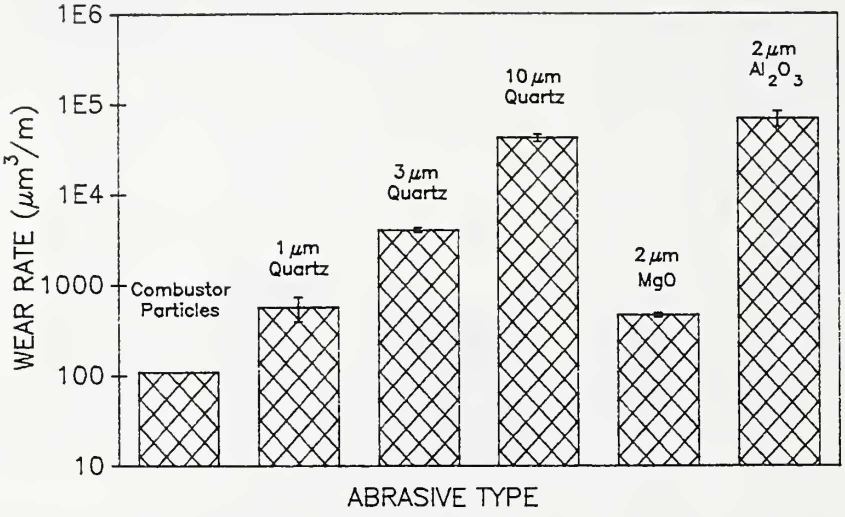


Fig. 14. Wear rate of 52100 steel pin. Effect of abrasive type and size compared at 5% concentration. 60% relative humidity.

the hardest mineral commonly present at significant concentrations in coal. At a particle size of 3 μm, quartz results in a wear rate approximately 40 times greater than the somewhat larger 5 μm combustor particles. The 3 μm quartz particles clearly constitute a material of far greater abrasivity than combustor particles.

Figure 14 also illustrates the influence of particle size and particle hardness on wear rate. The effect of particle size is demonstrated by the results for quartz particles. Wear rate is seen to increase significantly as the size of the quartz particles is increased from 1 μm to 10 μm. The highest wear rate among the materials tested was obtained with 2μm Al_2O_3 particles. Fortunately, Al_2O_3 and minerals approaching Al_2O_3 in hardness are likely to be present in most coals at only very small concentrations. MgO is seen to yield a lower wear rate than would be projected for quartz having the same 2 μm particle size. This is consistent with the fact that MgO is slightly softer than quartz. A more detailed discussion of the effects of particle hardness and size are given in a subsequent section.

Worn pin surfaces were examined by optical microscopy and SEM to obtain information on the operative wear mechanisms. Representative micrographs of scars after tests with no added particles, and after tests with combustion particles, mineral matter particles, and Al_2O_3 particles are shown in Fig. 15 - 18. An optical micrograph of the entire scar and an SEM micrograph of the scar edge at a higher magnification are shown in each

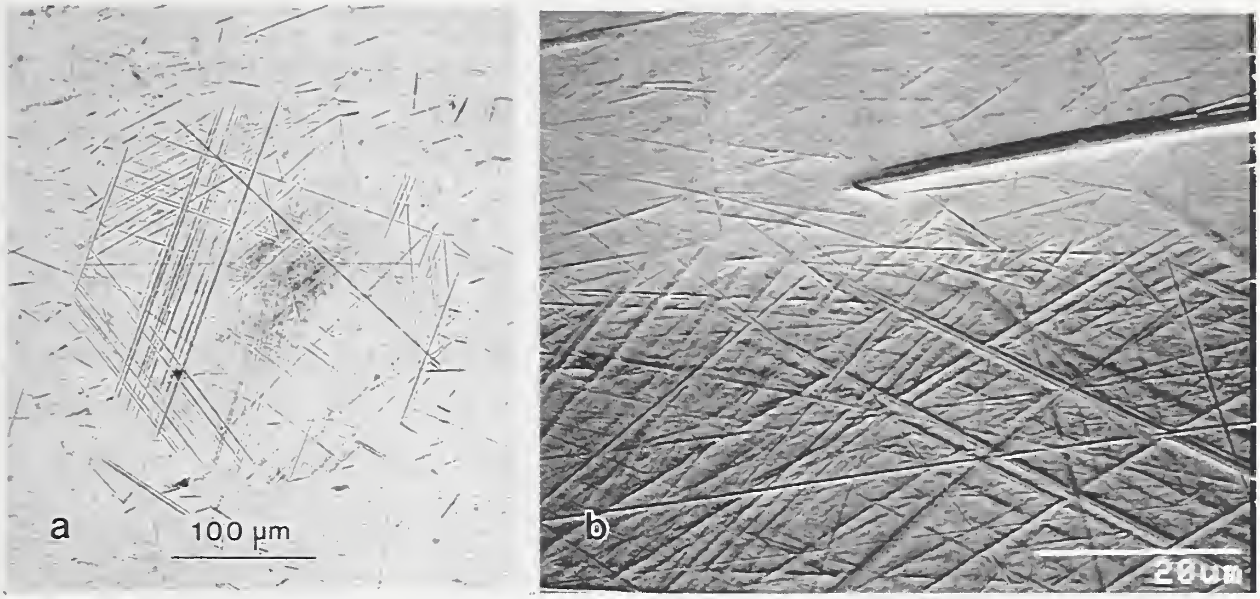


Fig. 15. Wear scar on 52100 steel pin after test with mineral oil (no added particles). (a) Optical micrograph and (b) SEM micrograph of scar edge.

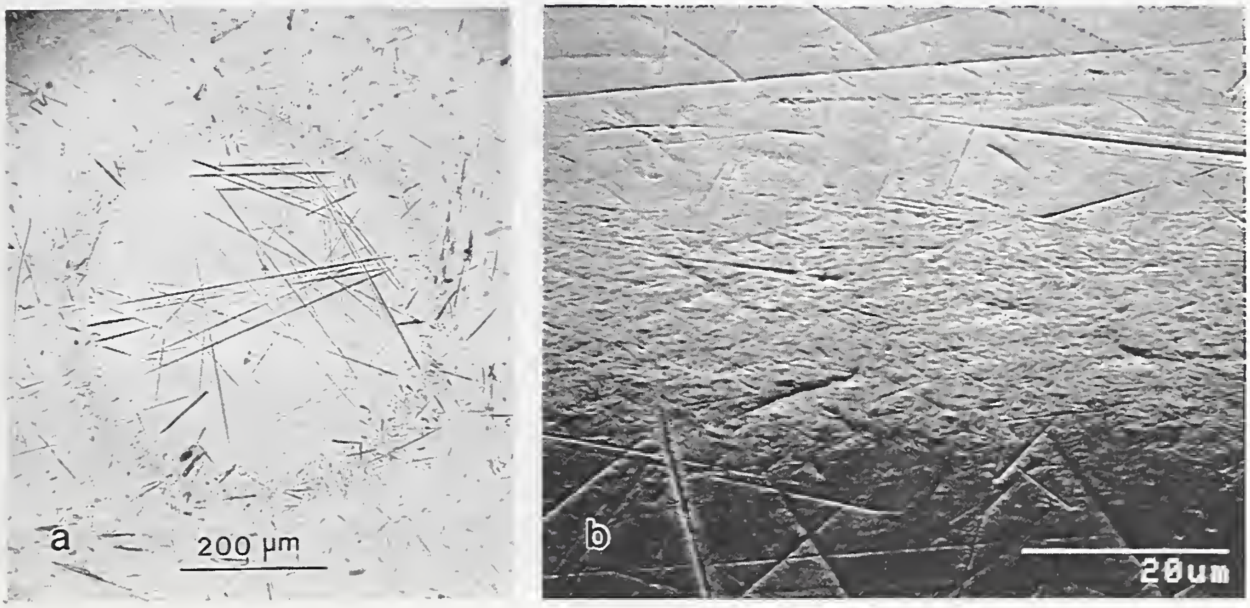


Fig. 16. Wear scar on 52100 steel pin after test with mineral oil containing 20 % combustor particles. (a) Optical micrograph and (b) SEM micrograph of scar edge.

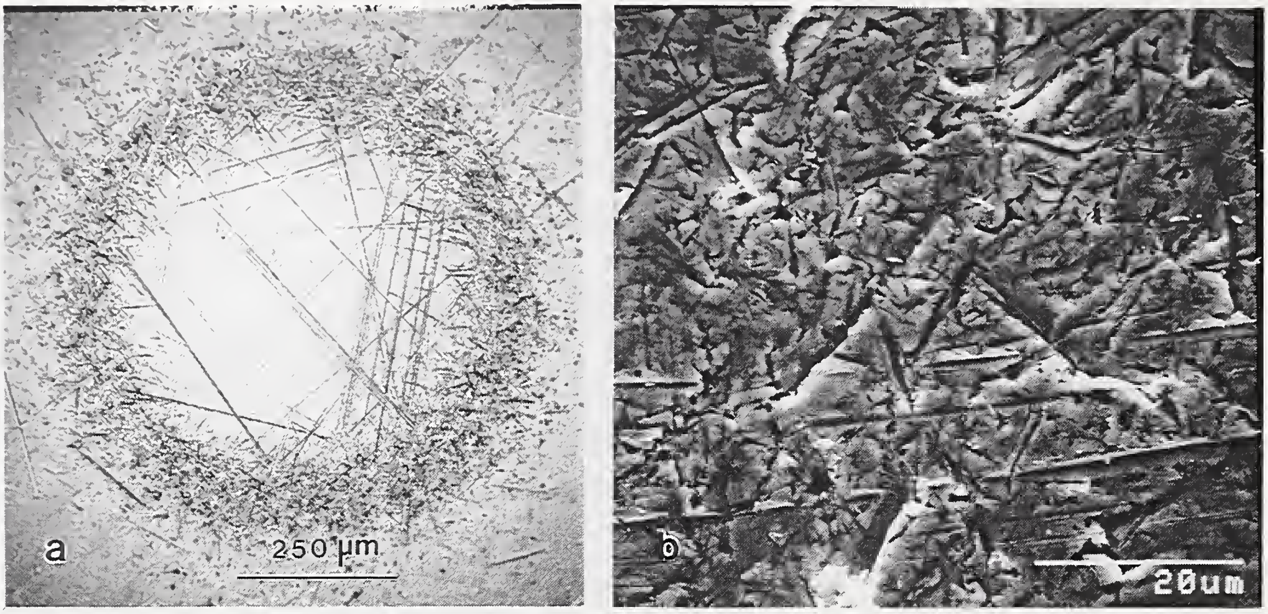


Fig. 17. Wear scar on 52100 steel pin after test with mineral oil containing 10 % mineral matter particles. (a) Optical micrograph and (b) SEM micrograph of scar edge.

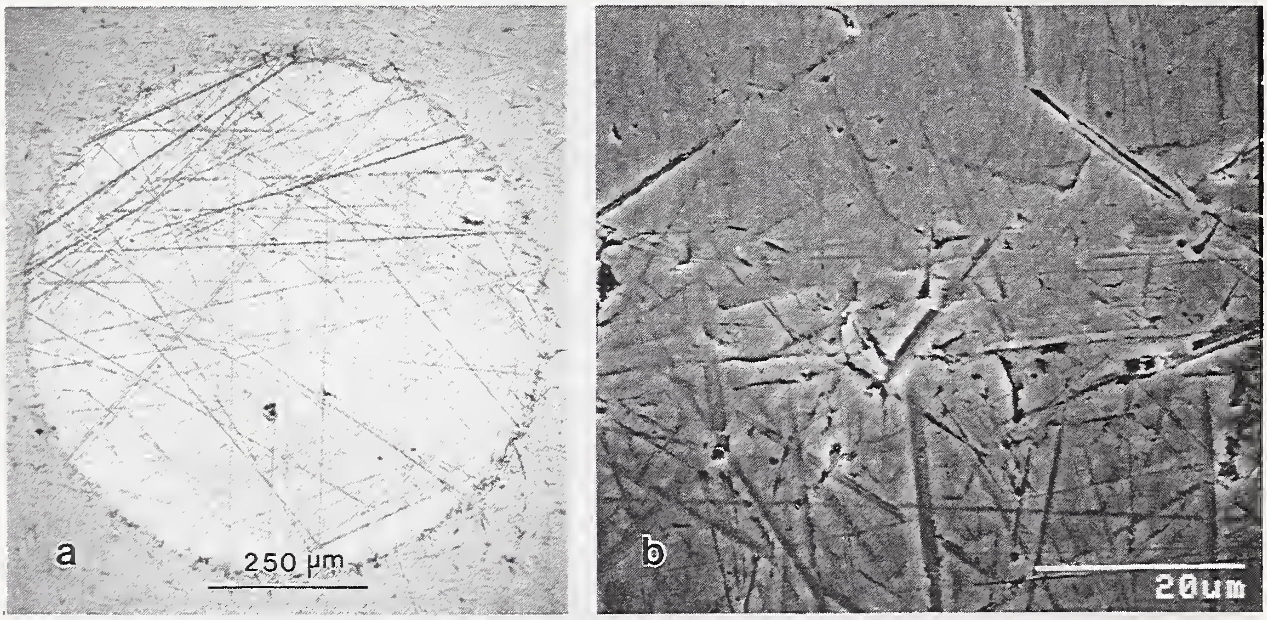


Fig. 18. Wear scar on 52100 steel pin after test with mineral oil containing 0.5% 2μm Al_2O_3 particles. (a) Optical micrograph and (b) SEM micrograph of scar edge.

case. Even with no added particles, Fig. 15, large scratches still occur. Most of the scratches extend entirely across the scar and are apparently caused by hard inclusions or second phase particles that are encountered in the 52100 steel disk. Thus, a certain amount of abrasive wear can occur even when particles are not present in the lubricant.

A dark region is seen at the center of the scar in Fig. 15a. This is due to the presence of a reaction film generated during sliding. The observation of such films is not unusual during sliding under boundary lubrication conditions. The film is formed as a result of chemical reaction between the metal surfaces, the lubricant, and air from the surrounding environment. The rate of reaction is greatly enhanced by high contact stresses and elevated local temperatures generated during sliding. Wear, often referred to as mild wear, occurs as a result of the formation and destruction of these films. Abrasion may cause the rapid removal of the film and subsequent exposure of fresh surface material to renewed reaction. This type of abrasive wear is usually associated with very small particles or relatively soft particles and is sometimes referred to as polishing wear. With more severe abrasion by large, hard particles, direct removal of surface material is dominant and the contribution to the total wear rate by the film wear process may be minor.

With 20wt.% combustion particles in the lubricating oil, Fig. 16a, no film is visible in the scar. As in the case of oil without added particles, large scratches are present due to inherent particles in the steel disk. In addition, there is a zone of damage around the outside perimeter of the scar. The SEM micrograph in Fig. 16b shows this region in more detail. The damage is seen to consist of small indentations introduced by particles trapped between the pin and disk during sliding. With mineral matter particles the zone is wider and the damage, shown in Fig. 17a and b, is visibly quite severe. With mineral matter particles the damage consists of relatively deep, angular indentations and gouges, compared to the much smaller, perhaps rounded indentations with combustor particles. The nature of the damage, of course, reflects the characteristics of the particles and hardness of the contacting surfaces. As was shown in Fig. 7, a large fraction of the combustor particles are spherical in shape, and would only cause angular indentations as a result of fracture or crushing. The mineral matter particles, shown in Fig. 6, are angular in shape. A zone of indentation damage also occurred with coal-fuel particles but was just barely detectable.

The damage due to combustor particles, Fig. 16, and mineral matter particles, Fig. 17, is less severe in appearance in the interior of the scar than at the periphery. Apparently, the particles do not have sufficient strength to resist crushing once they are exposed to the large, normal and shear stresses present within the contact. The very small crushed particles produce very fine scratches.

Figure 18a and b show the pin wear scar after a test with 2μm Al_2O_3 particles. As with the combustor and mineral matter particles, the damage is more severe at the periphery than in the interior of the scar. However, the stronger Al_2O_3 particles are more resistant to crushing and relatively deep scratches are also present within the scar.

Finally, it is interesting to note that the width of the zone of indentation damage provides a direct measure of the size of the largest particles in the collection capable of causing such damage. The width of the zone will, of course, depend on the geometry at the contact junction, which is determined by the diameters of the pin and wear scar.

4.2 Particle Concentration Effects

That particle concentration has a strong influence on wear rate has already been concluded in connection with Fig. 11 and 12. In this section a more detailed evaluation is given of this important variable. In Fig. 12 wear rate was seen to increase with increasing combustor particle concentration over the range extending from 0 - 20wt.%. However, the dependence observed in Fig. 12 is not linear. Wear rate increases rapidly at low concentrations and as 20wt.% is approached. The rate of increase is lower at intermediate concentrations.

The relationship between wear rate and particle concentration was also examined for mineral matter particles (Fig. 19), 3 μm quartz particles (Fig. 20), and 2 μm Al_2O_3 particles (Fig. 21). In each case, there is a high initial increase in wear rate followed by a lower rate of increase when approximately 2wt.% particle concentration is reached. Also, the initial rate of increase rises significantly as particle hardness increases. For example, at a particle concentration of 2wt.%, the wear rate is almost an order of magnitude greater with 2 μm Al_2O_3 particles than with 3 μm quartz particles. The behavior of the four different particle types is compared in Fig. 22 where the wear rate values are plotted on a log scale. At concentrations higher than 2wt.% the rate at which wear rate increases is approximately the same for the four particle types. If wear rate was proportional to the number of particles entering the contact, a linear dependence between wear rate and concentration might be expected. The relationship shown here is not linear, suggesting that the number of particles entering the contact is not directly proportional to concentration.

In relating the above results to the diesel engine it is important to realize that the engine presents a more complicated situation regarding particle concentration than does the pin-on-disk test arrangement. During fuel injection and combustion, raw coal particles and particles associated with combustion may settle on the thin oil film which is present on the cylinder wall. The effective concentration may in fact be very high since the particles, rather than being suspended in oil, are trapped on

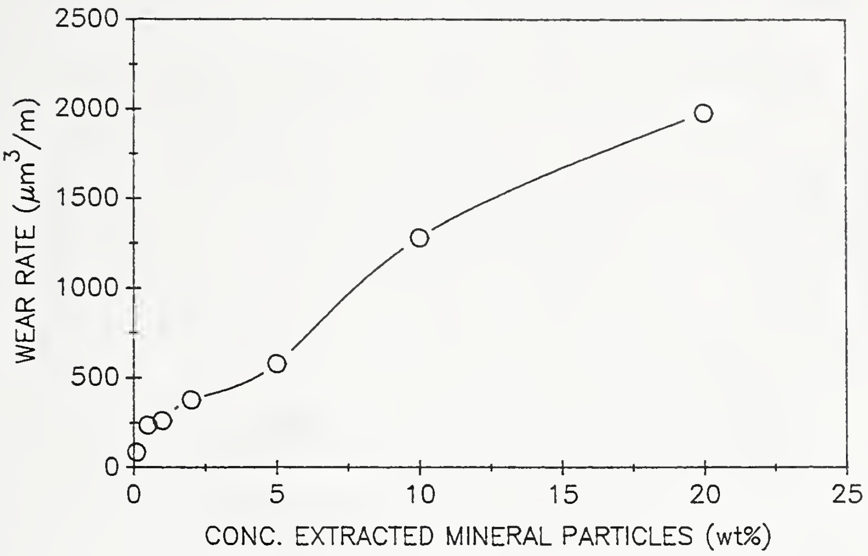


Fig. 19. Wear rate of 52100 steel pin as a function of concentration of mineral matter particles in mineral oil.

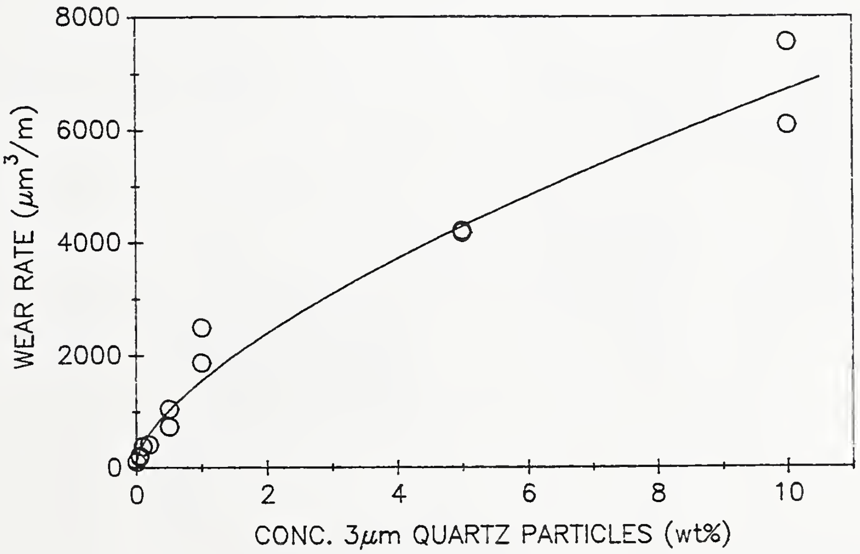


Fig. 20. Wear rate of 52100 steel pin as a function of concentration of 3 μm quartz particles in mineral oil.

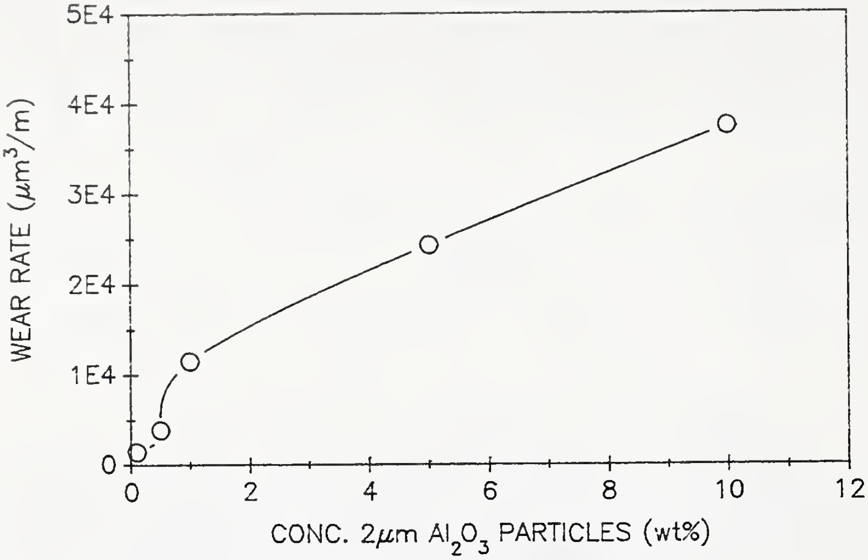


Fig. 21. Wear rate of 52100 steel pin as a function of concentration of 2 μm Al_2O_3 particles in mineral oil.

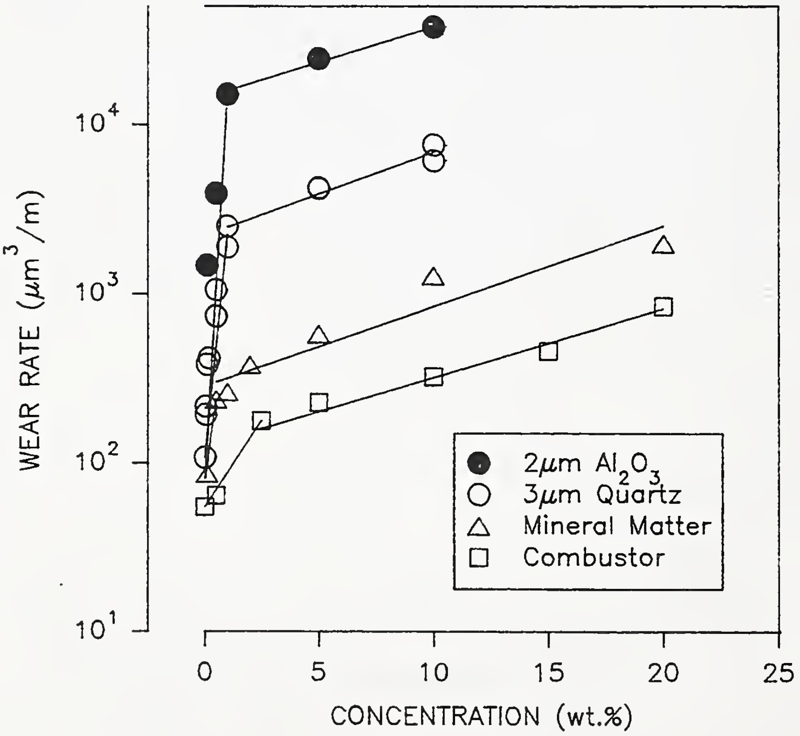


Fig. 22. Log_{10} of wear rate as a function of particle concentration.

an oil wetted surface. As the piston ring encounters these particles they may enter the contact and then on exiting become suspended in the oil. Thus, a continuous supply of particles deposited on the cylinder wall as well as particles accumulated in the oil can contribute to wear.

Recognizing that the effective concentration of particles at the piston ring and cylinder wall contact might be much higher than 10 or 20wt.% and that a substantial fraction of the particles consists of unburned coal, additional experiments were conducted to examine the effects of high particle concentrations. For these experiments, mixtures of coal and 1 μm quartz particles were employed. The quartz particle concentration was held constant at 5% while the coal particle concentration was varied from 0 to 30%. Thus, the total particle concentration ranged from 5% (no coal particles added) to 35% (5% quartz plus 30% coal particles). For comparison, data were also collected over the same concentration range with coal particles only added to the oil. The results are shown in Fig. 23. Below ~25% concentration the presence of coal particles is seen to have little effect on wear rate. This is because the coal-fuel particles themselves make only a small contribution to wear compared to the quartz particles, as is demonstrated by the coal-particles-only results. When the concentration of combined quartz and coal particles exceeds ~25%, the wear rate is seen to increase markedly. Data were not obtained above 35% since the mixture was no longer sufficiently fluid to spread over the surface of the disk during operation of the wear test machine.

It appears that the marked increase in wear rate above 25% total particle concentration is related to an effect of fluid rheology. At high particle concentrations the viscosity of the mixture was noticeably greater than at low concentrations; at 35% the mixture had a paste-like consistency. Since the concentration of hard particles was kept constant and the coal-fuel particles have only a small effect on wear rate, the increase in wear rate can not be related to an increase in the concentration of hard particles. However, the high fluid viscosity may result in a thicker film and cause more particles to enter the contact thereby increasing the abrasion rate.

Alternatively, because of the decreased fluid flow and smaller amount of oil available, it might be argued that inadequate lubrication caused the observed increase in wear rate. However, when only coal-fuel particles were mixed with mineral oil, no increase in wear rate was obtained at high particle concentrations. Thus, even with a very thick paste, there was sufficient oil present to provide lubrication, not to mention the possible solid lubricating properties of the coal particles themselves.[25] Apparently therefore, inadequate lubrication did not cause the increased wear rate.

The effect of relative humidity is also shown in Fig. 23. Higher relative humidities are seen to result in lower wear rates when the particle concentration is low. The effect of relative humidity diminishes at high particle concentrations. A similar

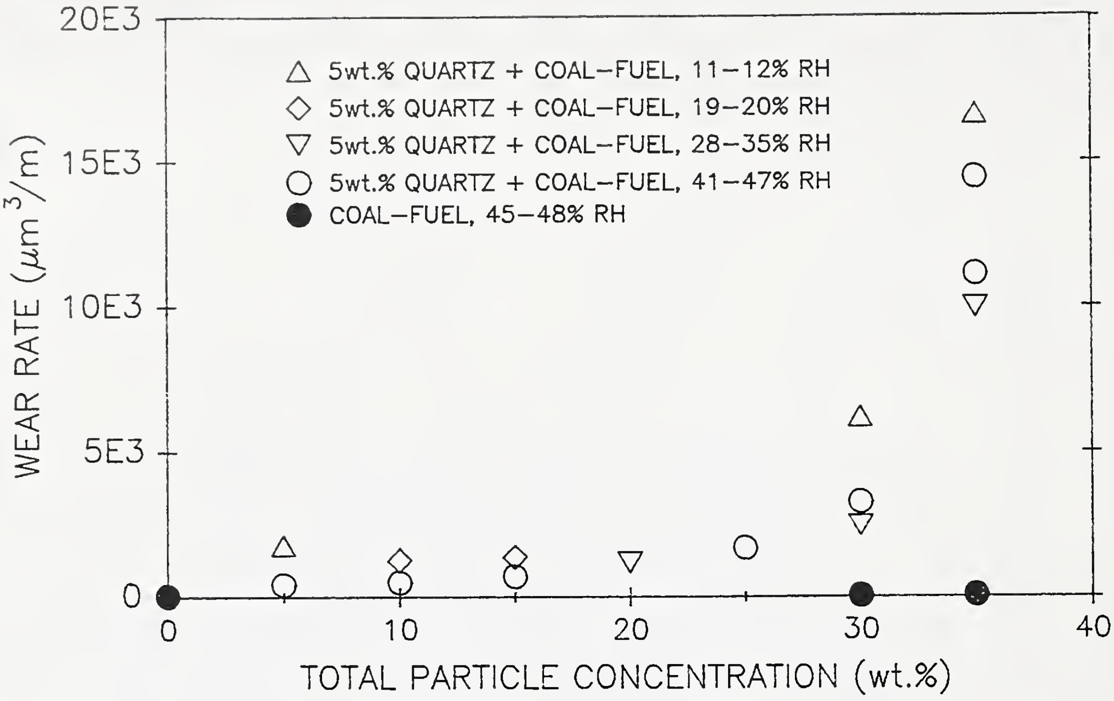


Fig. 23. Effect of coal-fuel particle concentration on wear by 5% 1μm quartz particles in mineral oil. 52100 steel pin specimens.

response was noted earlier in tests with turbine combustor particles, Fig. 12. Additional discussion of the influence of relative humidity is given in a subsequent section.

In addition to studying the effects of particle concentration in a fixed charge of mixture, experiments were also conducted in which the amount of mixture supplied to the disk was varied. The normal ~2ml charge, applied at the initiation of each test run, was well in excess of the quantity needed to produce a lubricating film on the disk surface. The exposed disk area was such that this amount of lubricant would result in an average film thickness of approximately 0.3 mm. The effective thickness was reduced by the action of the spreader shown in Fig. 1. However, the film was still sufficiently thick that substantial flow of lubricant occurred around the pin during sliding.

The effect of varying the quantity of lubricant-particle mixture is shown in Fig. 24. The mixture consisted of a 5% concentration of 2μm quartz particles in mineral oil. The wear rate is seen to be nearly constant when the quantity of mixture is greater than ~1.5 ml. When the quantity is reduced below that amount, wear rate is seen to increase, at first slowly and then rapidly, reaching a peak at about 0.5 ml. Wear rate then

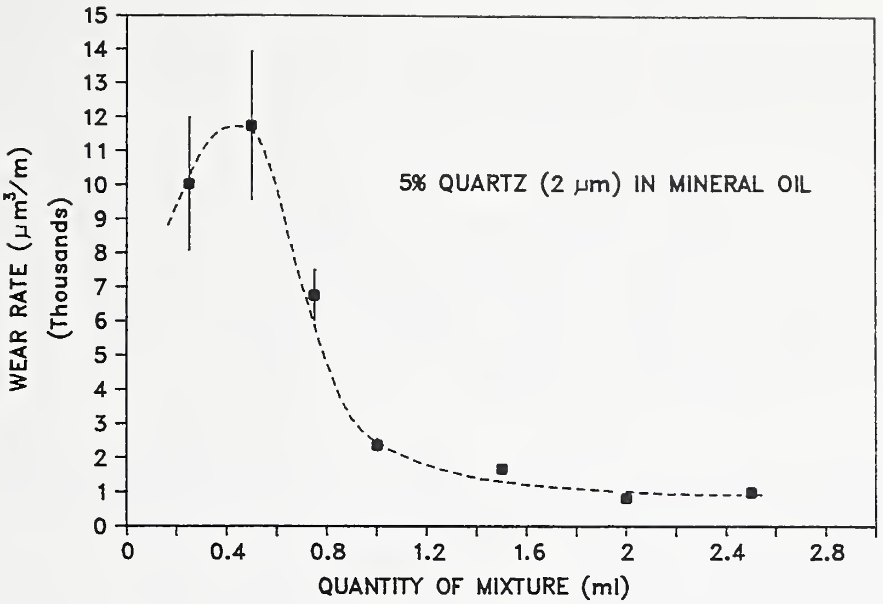


Fig. 24. Effect of quantity of mixture (5% Min-U-Sil in mineral oil) used for test on wear rate of 52100 steel pin.

decreases with further reduction in the quantity of mixture. The effect is quite significant in that the maximum wear rate, occurring at 0.5 ml, is an order of magnitude greater than is obtained with a charge larger than ~1.5 ml.

As was hypothesized above in connection with the influence of viscosity, the effect of quantity-of-mixture on wear rate may also be attributed to a change in the number of particles that enter the contact between the pin and disk. With the normal 2 ml charge, a condition is established whereby there is streamlined flow of fluid around the pin. Thus, particles entering this flow are swept around the contact rather than entering it. This is analogous to the situation in solid particle erosion where sufficiently small particles in a gaseous stream may be carried around an obstacle without impingement, therefore avoiding erosion.[26] Here, as the amount of fluid present is decreased, the flow is diminished, and an increasing number of approaching particles are potentially able to enter the contact. However, with continued reduction in the quantity of mixture, the decrease in the number of particles available becomes the controlling factor, resulting in a reduction in wear rate. With the test device used in this investigation, according to Fig. 24 that occurred at a charge of about 0.5 ml.

4.3 Effects of Particle Size and Hardness

It is well known that both particle size and hardness have a significant influence on the rate of abrasive wear. In two-body and three-body abrasive wear studies, wear rate is found to increase with increasing particle size until a size of about 100μm is reached; thereafter, wear rate becomes more-or-less independent of particle size. With respect to particle hardness, wear rate is low when particles are softer than the material being abraded, being essentially negligible for sufficiently soft particles in some cases. As the hardness of the particles approaches that of the material being abraded, wear rate increases significantly, typically reaching a high, constant value when the particle hardness exceeds that of the abraded surface.

The mean size of the coal particles employed as fuel in diesel engines is expected to lie in a range extending from about 5μm to perhaps 20μm.[27] As discussed earlier, the mean size of mineral matter particles in the coal-fuel and ash particles may be somewhat less than this. With respect to abrasive wear in the coal-fueled diesel engine, the mean particle size of interest will, therefore, lie in the range 20μm and less. Since this is well below the 100μm threshold, coal particle size can be expected to have an important bearing on engine durability.

The strong influence of particle size on wear rate has already been discussed in connection with Fig. 14. Data used in Fig. 14 for three different sizes of quartz particles are replotted in Fig. 25, along with the computed regression curve that is described by the relation,

$$\text{Wear Rate } (\mu m^3/m) = 587\ e^{0.44d} \qquad (1)$$

where d is the particle size in μm. Thus, increasing the particle size by a factor of 10 (from 1μm to 10μm) results in an increase in wear rate by more than 50 times. If the same relationship were to hold in an operating engine, it is clear that maintaining as small a particle size as possible is an important consideration.*

In addition to illustrating the influence of particle size, Fig. 14 also demonstrated the importance of particle hardness. Utilizing data for 2μm MgO and Al_2O_3 particles and computing a value from Eq. (1) for 2μm quartz particles, the dependence of wear rate on particle hardness is obtained. The results are

---

* Note, in the above treatment, particle size was expressed in terms of the mean size. A more accurate analysis would take into account the actual size distribution.

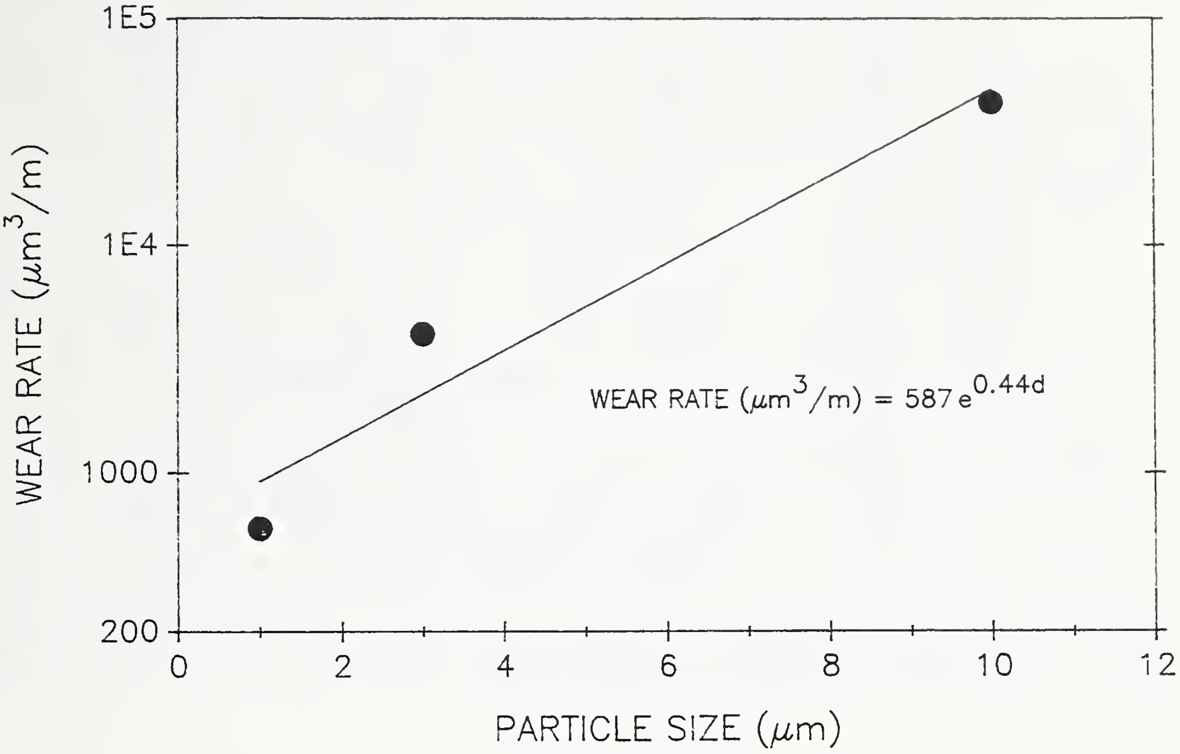


Fig. 25. Effect of quartz particle size on wear rate of 52100 steel pin.

plotted in Fig. 26 together with the regression curve that is given by

$$\text{Wear rate } (\mu m^3/m) = 39.3\ e^{0.00357h} \qquad (2)$$

where h is the particle hardness in kg/mm^2. Particle hardness, like particle size, is seen to have a very strong effect on wear rate. For example, doubling the hardness from 1000 kg/mm^2 (quartz) to 2000 kg/mm^2 (Al_2O_3) results in a 50-fold increase in wear rate. In terms of qualifying a particular source of coal for diesel engine applications, this result indicates that considerable emphasis should be placed on the hardness of the mineral content of the coal and associated combustion particles. Thus, a high ash coal with relatively soft resultant particles, be they unaltered mineral particles or combustion particles, might be more acceptable than a low ash coal yielding hard particles.

The wear rate with the coal-fuel particles, despite the low hardness of coal compared to 52100 steel, is higher than

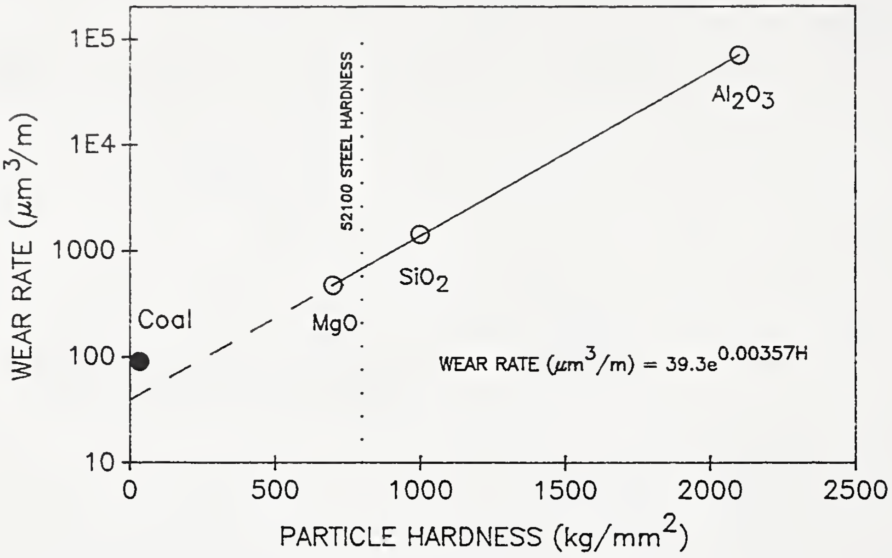


Fig. 26. Effect of particle hardness on wear rate of 52100 steel pin. 5% concentration, 2μm particles.

predicted by Eq. (2). This is due, at least partly, to the presence of hard mineral particles in the coal. In any case, there is no reason to expect that the soft particle response should be the same as that for hard particles. Additional studies are needed to examine the soft particle regime.

The above results on the effect of particle hardness can be compared with those reported in the literature. In general, it is found that wear rate decreases rapidly when the hardness of the abrasive particles is less than about 0.8 times the hardness of the surface being worn.[28-30] On the other hand, when the hardness of the abrasive exceeds that of the surface being worn by more than a factor of about 1.2, wear rate is relatively high and remains constant independent of abrasive hardness.[28,30] It is the latter observation that is of particular interest here. In Fig. 26 there is no indication that wear rate approaches a constant, asymptotic value for abrasives that are much harder than 52100 steel (810 HK).

In addition to this investigation, two other studies were found that reported a continuously increasing wear rate without asymptotic approach to a constant value with increasing particle hardness. In both of those investigations, wear behavior was studied at lubricated contacts with hard particles in the lubricant. One investigation[31] dealt with hydrodynamic lubrication and the other[32] with boundary lubrication conditions. In neither of these investigations was an explanation given for the difference between the observed wear behavior and that generally reported in the literature.

It appears that the wear behavior is related to the nature of the abrasive wear test employed. When the wear rate remains constant for abrasives that are more than 1.2 times harder than the surface being abraded, a so-called low stress abrasive wear test was employed. In a low stress test the abrasive particles are not subject to appreciable crushing in the contact. This is usually a consequence of the particles being supported by a relatively soft counterface material, for example, particles bonded to paper or cloth, can satisfy this condition. As long as the particles are harder than the material being abraded, wear rate will be independent of hardness. High stress abrasion refers to a condition where the particles are likely to be crushed in the contact. This is the condition that probably exists at lubricated contacts utilizing relatively hard metal and ceramic bearing elements and is the condition that prevailed in the present experiments. Wear rate will then depend on the ability of the particle to resist crushing. Crushing strength for many abrasives is closely related to hardness. The increase in crushing strength apparently explains the continued increase in wear rate with increasing particle hardness observed in Fig. 26.

4.4 Other Effects

4.4.1 Relative Humidity

Reference has already been made to the influence of the relative humidity on wear rate in connection with Figs. 12 and 23. There, it was seen that higher wear rates were associated with lower relative humidities. The effect of relative humidity was studied in more detail for the case of 1μm quartz particles. The results are shown in Fig. 27. With an increase in relative humidity from about 30% to 60%, the wear rate is seen to decrease by approximately a factor of six.

With the test equipment employed there was no facility for controlling relative humidity. Variations in relative humidity were the result of prevailing weather conditions, although air conditioning usually limited the maximum value to about 60%. Since the particles were suspended in oil and the disk and pin specimens were also covered with oil throughout the test, it must be concluded that exposure to water occurred by means of the oil film. The maximum solubility of water in mineral oil is limited to 1 or 2% at 24°C. During sliding, however, considerable stirring and turbulent mixing takes place with the result that aeration of the oil almost certainly occurs. Thus, exposure to water dissolved in the oil and in entrained air both occur.

Larsen-Basse[33] investigated the effect of relative humidity on abrasive wear and obtained quite different results. His experiments were conducted in air without lubricants using a three-body abrasive wear test. Silicon carbide particles were employed as the abrasive. When the humidity was above ~50%, he

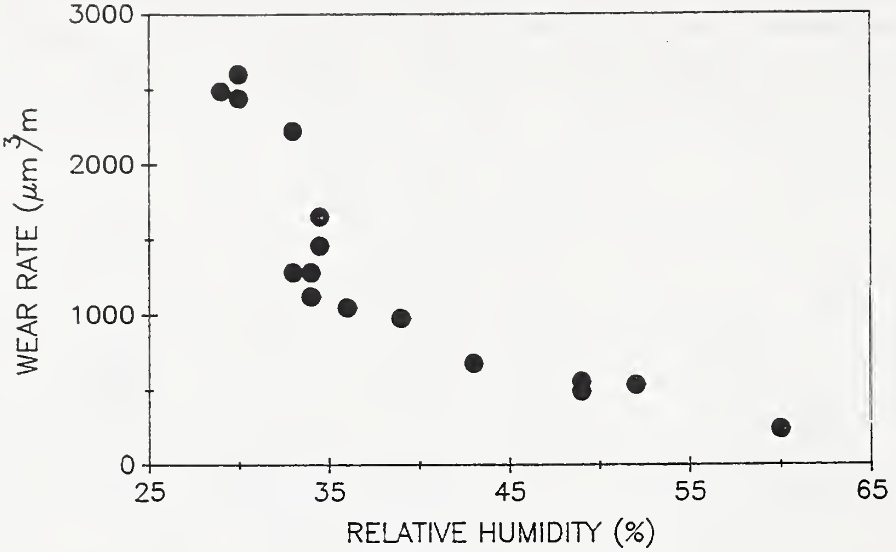


Fig. 27. Effect of relative humidity on wear rate of 52100 steel pin with 1% 1μm quartz particles in mineral oil.

found that wear rate increased with increasing humidity. Below 50%, changes in relative humidity had little effect. This is opposite to the dependence observed in these experiments. Larsen-Basse determined that the average size of used particles collected from the test was smaller for high humidities than for low humidities and concluded that the particles were more easily fractured at high humidities. This, he hypothesized, produced sharper particles and, consequently, a higher wear rate. The production of sharp particles would certainly be important if the original particles were not sharp.

In the present study, it could also be assumed that exposure to water led to a reduction in fracture strength of the particles. Thus, wear rate would decrease at high humidities because the particles were more easily crushed resulting in a smaller effective particle size. This explanation is consistent with the strong influence that particle size was found to have on wear rate.

On the basis of this explanation, the effect on wear rate would depend on the sensitivity of the particular type of abrasive particle to the presence of water. Wear rate would not be affected for particles that were insensitive to water.

Finally, there is no obvious explanation for the reduction in the influence of relative humidity at high particle concentrations shown in Figs. 12 and 23.

4.4.2 Additives

Reported results regarding the effect of lubricant additives on wear by abrasive particles is varied. In some cases additives have been found to decrease wear rate, in others there was no effect, and in still other cases an increase was observed.[16] Explanations for the contrasting behavior differ and depend on the nature of the additive and the contact conditions. Additives that control fluid rheology are likely to lead to a different response than those that affect extreme pressure (EP) characteristics. In the present work, preliminary investigations were conducted to determine the effect of a widely used motor oil additive, zinc dialkyldithiophosphate (ZDDP).

To assess the effect of ZDDP tests were conducted comparing mineral oil containing 0.2% ZDDP with mineral oil containing no ZDDP. The effect on abrasive wear rate was determined by mixing these oils with 5% combustor particles. The single pin test configuration was used in these experiments, and the disks were of O-2 tool steel.

Results for four different lubricant conditions are compared in Fig. 28. The addition of ZDDP to mineral oil (without particles) is seen to decrease wear slightly. This is to be expected since the contact stresses are quite high, and sliding is in the boundary lubrication regime as described earlier. Thus, the anti-wear properties of ZDDP are active. With 5% combustor particles in the mineral oil the wear rate is increased

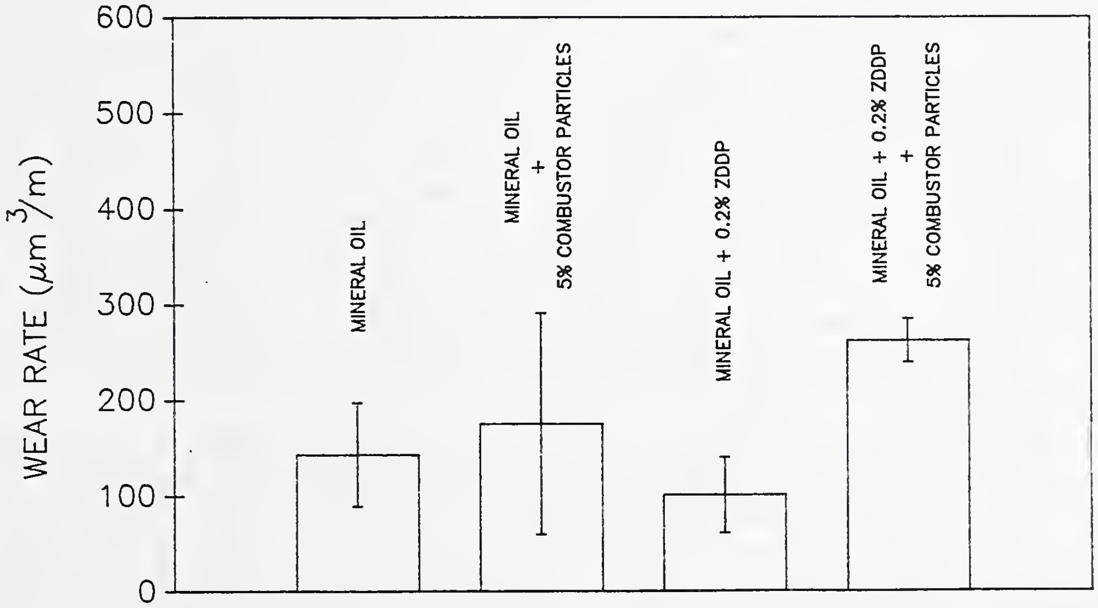


Fig. 28. Effect on wear rate of 52100 steel pin of the addition of 0.2% ZDDP.

substantially, as expected. When the combustor particles are added to mineral oil containing ZDDP an even larger increase in wear rate results. That ZDDP causes such an increase can be explained as follows. One mechanism by which the additive imparts improved protection is through reaction with the steel surface to produce a soft, shearable film that provides protection against severe deformation wear. However, removal of this film by abrasion exposes fresh metal surface for reaction, leading to enhanced tribochemical wear, the net effect being an increased abrasive wear rate. Of course, other mechanisms could occur and be responsible for the increased wear rate. For example, the additive could improve the efficiency of chip formation, as is experienced with sulfur containing additives in grinding fluids.[34]

4.4.3 Embedment

As described in the section on experimental procedure, by conducting a pretest without particles added to the oil, it was possible not only to establish the baseline wear rate value but also to monitor changes in the condition of the disk that might influence the wear rate of the pin. An increase in disk surface roughness or, especially, the embedment of particles can lead to significantly higher wear rates. In general, large changes in the baseline wear rate were not experienced when a previous test had been run with coal-fuel, mineral matter, combustor, or quartz particles. However, after a test with Al_2O_3 particles, significantly higher pin wear rates are obtained in subsequent tests without particles. Examples of this effect are illustrated in Figs. 29 and 30. Fig. 29 shows the results of a sequence of tests alternating between oil without particles and oil with particles. The first test in this sequence was conducted on a newly finished disk surface using oil without added particles. For the second test, 0.1% 2μm Al_2O_3 particles was added to the oil. The next test was conducted without added particles, and so forth as indicated in the figure. Compared to the first test on the newly finished disk surface, all succeeding tests without particles, which now follow tests with particles, yielded significantly higher wear rates. In fact, the increase was by more than an order of magnitude. This high "baseline" value is seen to depend very little on the particle concentration used in the previous test, at least for the concentrations of 0.1% and 0.5% studied.

Figure 30 shows the results for a second series of tests. All of the tests were conducted without particles added to the oil. Prior to this series, the disk had been used for a test with 5% 2μm Al_2O_3 added to the mineral oil. Starting at a high value, the wear rate is seen to decrease with each succeeding test until the seventh test, after which there is little additional change. However, even after nine tests the wear rate is still significantly higher than the usual baseline value obtained with a freshly prepared disk surface.

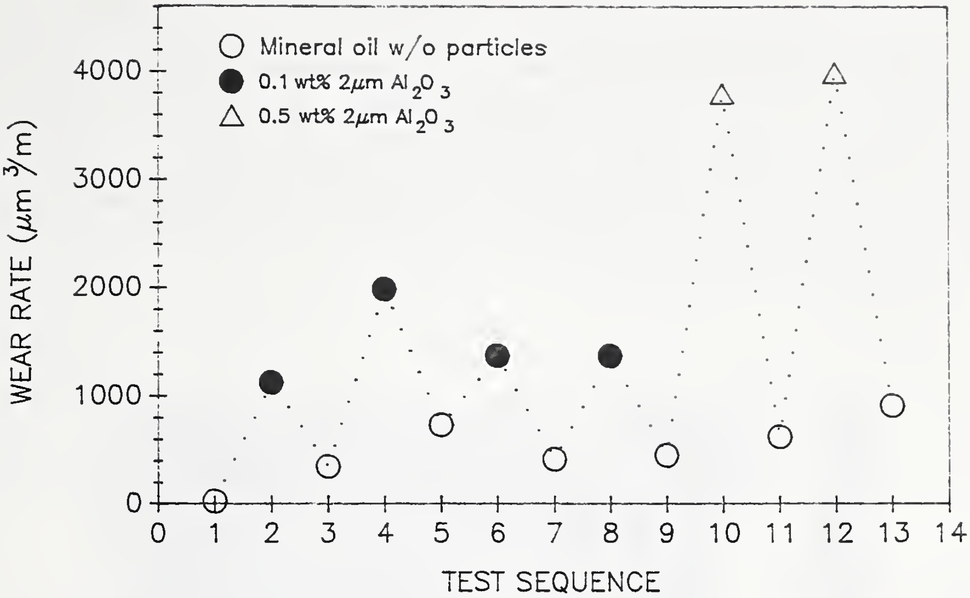


Fig. 29. Wear rate of 52100 steel pin in alternating tests with and without the addition of 2μm Al_2O_3 particles to mineral oil showing the effect of embedment of particles in disk surface.

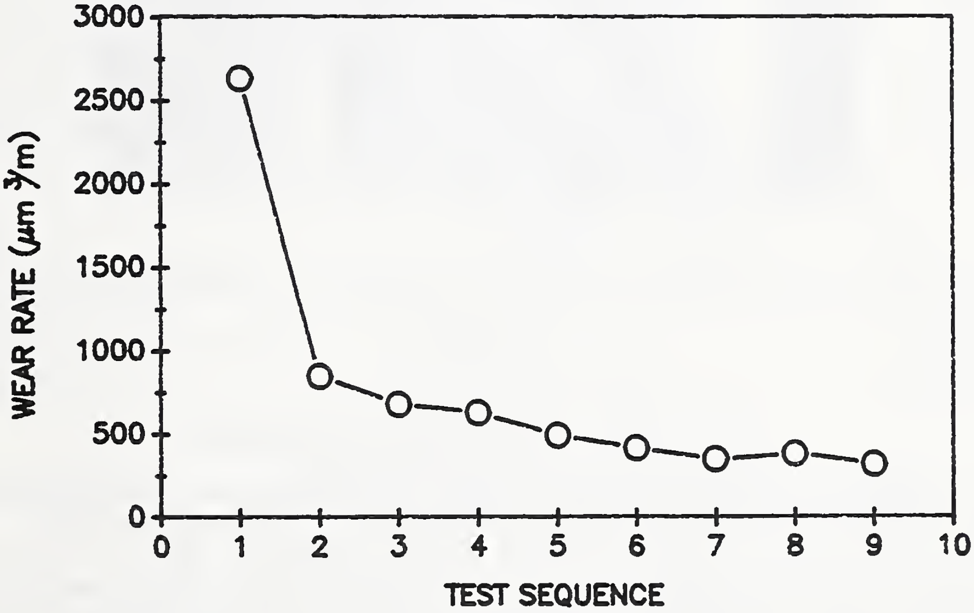


Fig. 30. Wear rate of 52100 steel pins in sequence of tests without added particles. Follows test with 5% 2μm Al_2O_3 particles in mineral oil that resulted in the embedment of particles in the 52100 steel disk.

That the marked increase in the baseline wear rate was due to embedment was demonstrated by the observation of Al_2O_3 particles in the disk. An example of an embedded particle is shown in Fig. 31. The high hardness of Al_2O_3 relative to the 52100 steel disk is apparently an important factor encouraging embedment. Among the other particles mentioned above only quartz is harder than the 52100 steel disk, but only moderately. As noted, there was no evidence for embedment of quartz, or of the other particulate materials.

Fig. 31. SEM micrograph of Al_2O_3 particle embedded in 52100 steel disk.

4.5 Wear of Selected Materials

In earlier discussion it was indicted that conventional piston ring and cylinder liner materials did not provide satisfactory wear lives by very large margins during coal-fuel operation. Conventional materials range from relatively soft gray cast iron to much harder chromium plating. Despite the fact that the latter material may approach quartz in hardness, it still exhibits an extremely high rate of wear during coal-fuel operation.[3]

In order to study the effect of hardness and other properties on wear rate, tests were conducted on a variety of different pin materials, including pure metals, metal alloys, ceramics, cermets and glasses. The materials studied are listed in Table 6. Two different types of particles were employed in these tests: GE filter residue and extracted mineral matter. The characteristics of these particulate materials are given in the earlier Particle Properties section. The filter residue gives an approximate simulation of the particles that enter the piston ring and cylinder wall contact in an operating engine. The mineral matter particles produce what is perhaps a worst case situation with respect to exposure to abrasive particles associated with Blue Gem coal-fuel. The filter residue was mixed at a concentration of 50% with mineral oil, leading to a final particle concentration of about 25%. The mineral matter particles were mixed with mineral oil at a concentration of 20%.

Table 6. Pin Materials

Material	Description*	Hardness (HK_{200})
Ta	(C) 99.5% pure	174
Mo	(C) 99.5% pure	267
Ni	(C) 99% pure	294
W	(C) 99.98% pure	496
316 stainless	(B) annealed	253
K-Monel	(B) age hardened	426
52100 steel	(B) bearing ball	800
440C steel	(B) bearing ball	834
M50 steel	(B) bearing ball	780
Black Glass	(B) 69.7% SiO_2; 3.4% CaO; 3.2% BaO; 15.2% Na_2O; 0.8% K_2O; 1.3% B_2O_3; 6.4% MnO_2	469
Fuzed Quartz	(C) -	590
Zirconia	(C) Sintered TZP	1090
Silicon Nitride	(B) Toshiba	1650
WC-6Co	(B) Carboloy 44A	1660
Sapphire	(B) -	1780

*(B) - Ball and (C) - Conical Pin

The three-pin configuration was employed in these tests. As indicated in Table 6, both spherical and conical pins were employed. Also, for these experiments the pins were "preworn" by polishing on ¼μm diamond grit to produce a flat scar with a diameter of 0.75 - 1.00 mm. The load applied to each pin was 5.6 N, resulting in a contact pressure comparable to the maximum ring contact pressure in an operating diesel engine. The disks were of 52100 steel. The remaining test conditions are given in Table 1.

The pin hardness values listed in Table 6 were determined by means of Knoop indentation at a load of 2N. The measurements were made in the wear scar surface after tests with filtrate particles.

The wear rates of the different pin materials obtained with the 1:1 mixture of filter residue and mineral oil are plotted in Fig. 32 as a function of pin hardness. Wear rate is not a simple function of hardness but is seen to depend strongly on other properties in addition to hardness. For example, the wear rate of K-Monel is substantially greater than that of Mo, yet Mo is softer than K-Monel. On the other hand, it is clear that in general the wear rate is significantly lower for materials that are harder than approximately 1000 kg/mm2. As noted earlier, it is a general rule that the rate of abrasion decreases markedly when the surface being abraded is greater than about 0.8 times the hardness of the particles.[28-30] Thus, the results presented in Fig. 32 are consistent with abrasion by particles no harder than quartz (~1000 kg/mm^2).

For the hardest pin materials—zirconia, silicon nitride, sapphire, and WC-6Co—the amount of wear was extremely small. For sapphire, wear could not be measured in terms of the actual removal of a layer of material from the surface even after a sliding distance exceeding $3X10^4$m. Small scratches that were present at the initiation of sliding could still be distinguished

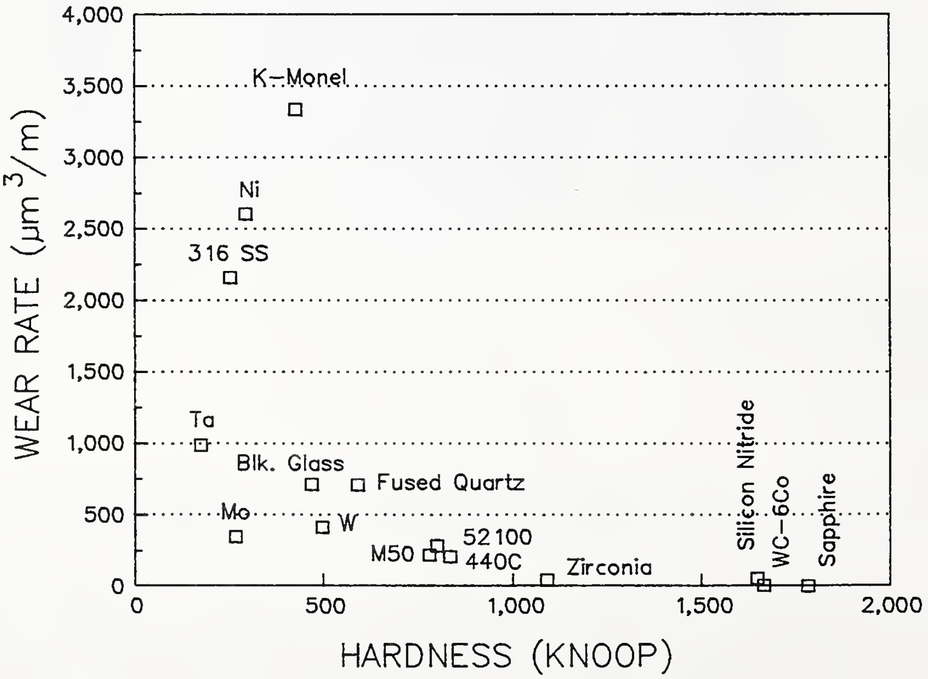


Fig. 32. Wear rates for different pin materials against 52100 steel disk lubricated with 1:1 mixture of mineral oil and oil filter residue from diesel engine run on coal-fuel.

on the sapphire surface. However, there were many new scratches suggesting that after sufficiently prolonged sliding an amount of wear would occur that could be measured.

The wear rate of WC-6Co was extremely low ($5\mu m^3/m$) while the wear rates of both silicon nitride and zirconia, though still not large, were approximately an order of magnitude higher. The silicon nitride and WC-6Co pins were about equal in hardness, so hardness is not the source of the difference in their wear rates. It is also unlikely that the difference in wear rates is associated with the greater toughness of WC-6Co, since there was no evidence of fracture associated with the scratches. In fact, this lack of fracture suggests that abrasion occurred primarily within the ductile regime for both silicon nitride and WC-6Co.[35] The larger wear rate of silicon nitride could be explained by microstructural differences, namely the fine grain size of the silicon nitride material compared to WC-6Co, or by a tribochemical process. Tribo-oxidation has been found to play an important role in the friction and wear of silicon nitride[36], and it may make a significant contribution here. Also, it may be noted that zirconia, which is significantly softer than silicon nitride and only slightly tougher (K_{IC} = 7 $GPa \cdot m^{1/2}$ for the silicon nitride and 8.5 $GPa \cdot m^{1/2}$ for the zirconia used in these experiments), exhibits about the same wear rate as silicon nitride. This result provides further support for the supposition that a tribochemical mechanism is responsible for the higher wear rate of silicon nitride.

Although there was no general evidence of fracture associated with the abrasion of WC-6Co, damage existing prior to sliding did produce a pronounced effect. Figure 33a shows a Vickers hardness indentation introduced before sliding commenced, and Fig 33b shows the same indentation after sliding for a distance of $3X10^4$m. It is clear that microcracks in the vicinity of the indentation have led to more extensive damage during sliding. For sapphire, which is considerably more brittle than WC-6Co, even greater damage was observed at hardness indentations after sliding. In a practical application, damage as a result of machining could lead to rapid degradation of the surface during subsequent exposure to wear. Clearly, initial surface integrity can be an important factor with respect to wear, and it is especially critical for materials with low fracture toughness.

In Fig. 34 wear rate is plotted as a function of specimen hardness for tests with 20wt.% extracted mineral matter particles in mineral oil. On average, the wear rate is several times higher than with the coal-fueled diesel particles (Fig. 32). This can be attributed to a larger mean particle size and almost certainly to a higher concentration of hard particles for the extracted mineral matter. Nevertheless, on an absolute scale the wear rate with mineral matter particles is still quite low for materials that are harder than approximately 1000 kg/mm^2. For sapphire it is interesting that, whereas little wear could be detected with diesel filtrate particles, the wear rate is now

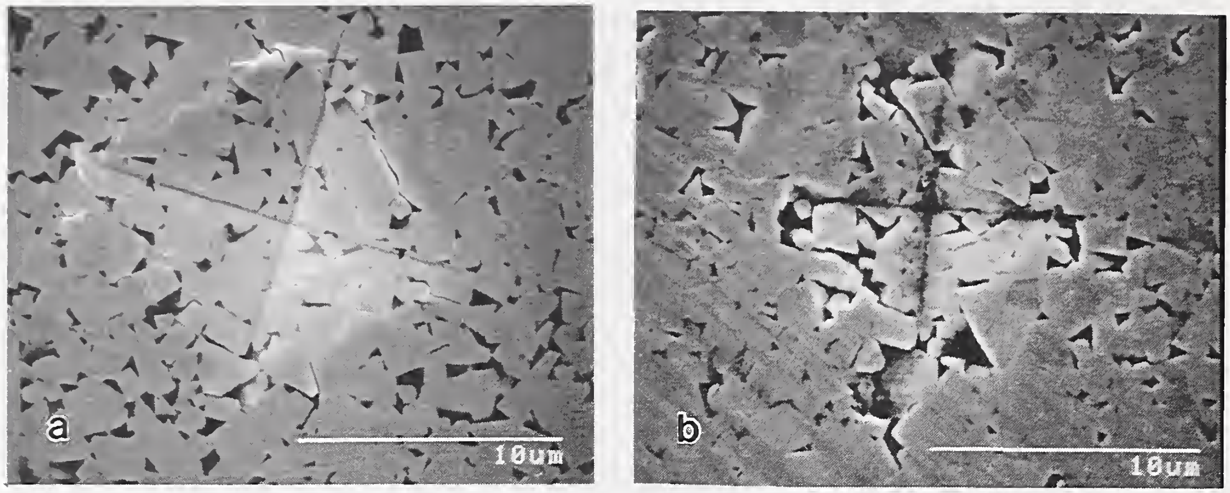


Fig. 33. Vickers hardness indentation in WC-6Co pin. (a) Before test and (b) after sliding $3x10^4$m with lubricant consisting of 1:1 mixture of mineral oil and oil filter residue from diesel engine operated on coal-fuel.

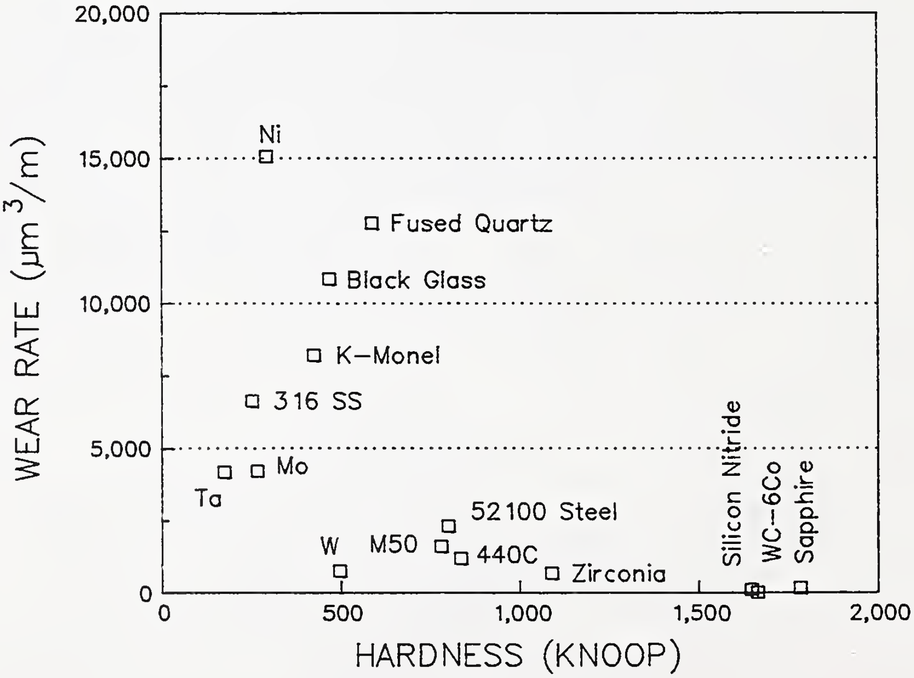


Fig. 34. Wear rates for different pin materials against 52100 steel disk lubricated with mineral oil containing 20% mineral matter particles.

greater than for either silicon nitride or WC-6Co. Examination of the worn surface of sapphire revealed evidence of lateral fracture in the vicinity of scratches. This was not observed for the silicon nitride and WC-6Co specimens. With the larger particles present in the extracted mineral matter material, the stresses were apparently high enough to initiate fracture in the more brittle sapphire. Thus, at least for some particles, abrasion occurred in the lateral fracture mode.

As mentioned earlier, the wide variation in wear rate values seen in Fig. 32 and 34 does not indicate a simple dependence on hardness. The large variation should not be surprising since the materials studied represent significant differences in mechanical characteristics and microstructure; moreover, abrasion was by a collection of different types of particles with different strength characteristics. In addition, modes of wear other than abrasive wear (deformation, fatigue, and tribochemical modes) contribute in varying measure to the loss of material. Also, when the particles are softer than the contacting surface, tribochemical and deformation wear processes and not direct abrasion will prevail. Thus, the inverse relationship between hardness that is often observed for pure metals and annealed alloys[28,30] can not be expected to hold. Nor should one expect the wear rate of the ceramic and glass materials to follow such relations as $K_c^{-5/8}H^{-1/2}$ derived by Evans and Marshall[35] or $K_c^{-3/8}H^{-1/2}$ obtained for tougher cermets[37].

4.6 Wear of WC-6Co

Because cemented tungsten carbide has been identified as an important potential candidate for coal-fueled diesel engine applications, additional experiments were conducted on the WC-6Co material. Cemented carbides combine high hardness, significant toughness, and excellent resistance to abrasive wear. They are extensively used in such demanding applications as machining and rock drilling. Cemented carbides can be employed in sintered-monolithic form or as coatings. Commonly used compositions consist of 6 to 12% cobalt binder with tungsten carbide grains. A variety of other compositions are available, however, and selection is based on the requirements of the specific application. In general, abrasive wear resistance is dependent on composition, the concentration of binder phase and carbide grain size.[38,39]

In the present investigation the abrasion rate of WC-6Co was determined for four different types of particles in mineral oil. The particles were 2μm quartz, 1μm and 3μm Al_2O_3, and 1μm diamond particles. To account for the different densities of these particulate materials, the same volume concentration (40%) of each particle type was used. The tests were conducted without a preworn flat on spherical WC-Co pins. A disk of 52100 steel disk was used. Because of the great differences in wear rates, rather than utilizing a fixed sliding distance, the tests were

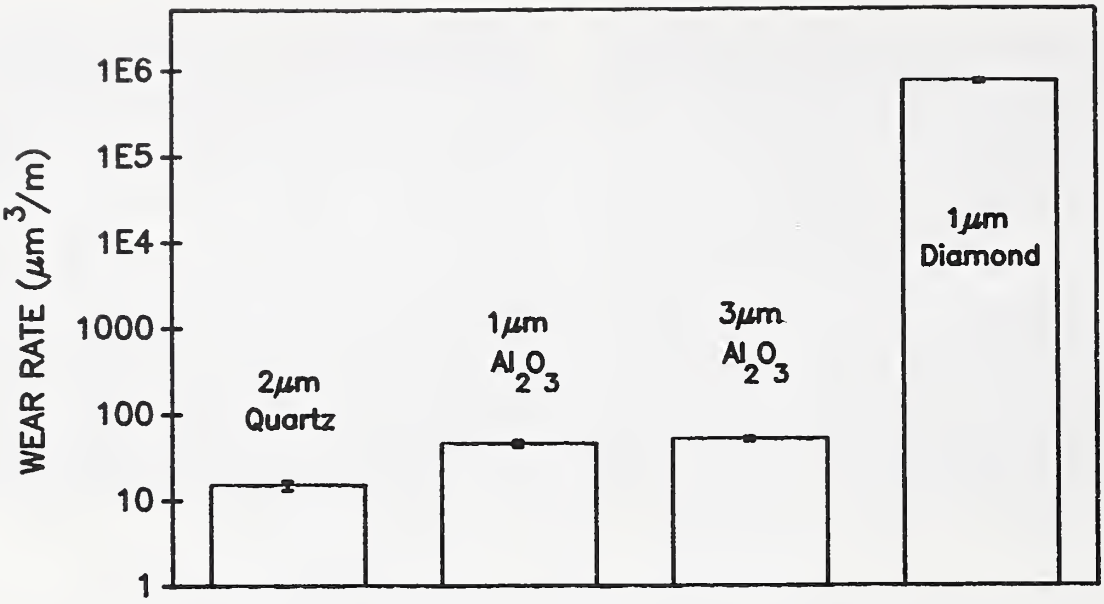


Fig. 35. Wear rate of WC-6Co pin by different particles in mineral oil at a concentration of 40 volume percent.

terminated when a scar diameter of approximately 0.4mm was reached. The remaining test conditions are those given in Table 1.

The results are shown in Fig. 35. As expected, the lowest wear rate ($15\mu m^3/m$) was obtained with the quartz particles. The wear rate with Al_2O_3 particles was higher by about a factor of three. However, with diamond particles the wear rate ($7X10^5\mu m^3/m$) was more than four orders of magnitude higher than with quartz or Al_2O_3. Quartz having a hardness of approximately 1000 kg/mm^2 is appreciably softer than WC-6Co, which had a Knoop hardness of 1660 kg/mm^2. Al_2O_3 is somewhat harder than WC-6Co; however, WC-6Co is a composite and the individual WC grains have a hardness that is similar to that of Al_2O_3. Diamond, of course, is substantially harder than WC and this, together with its high strength, accounts for its markedly higher abrasivity.

The abrasive wear mechanism was with diamond particles was also different from that with quartz and Al_2O_3. An SEM micrograph of the WC-6Co pin surface worn with diamond particles is shown in Fig. 36. Relatively deep scratches are present and pits are observed along the scratches, indicating fracture of WC grains. For quartz and 1 μm Al_2O_3, Fig. 37 and 38, respectively, only occasional scratches are seen. The majority of the scratches were apparently too small to be detected. For larger, $3\mu m$ Al_2O_3 particles more scratches were observed, but the scratches were still quite shallow compared to those produced by

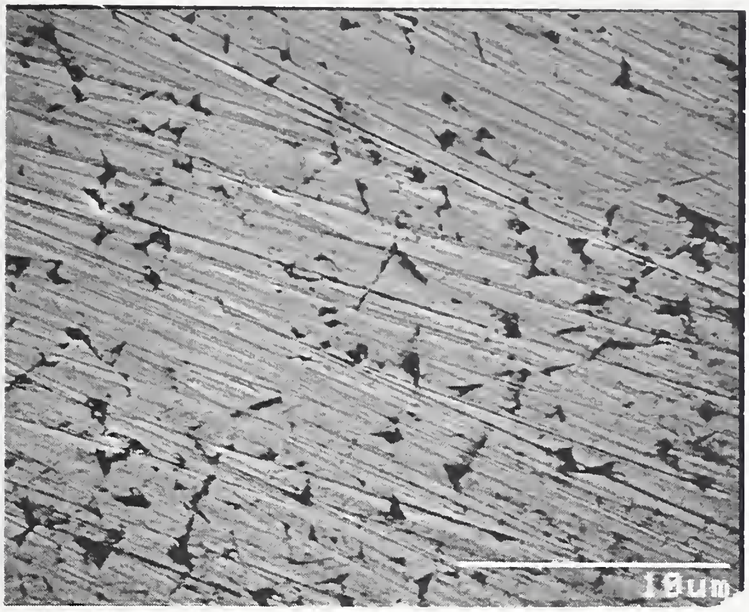


Fig. 36. SEM micrograph of WC-6Co pin surface after wear by 1 μm diamond particles.

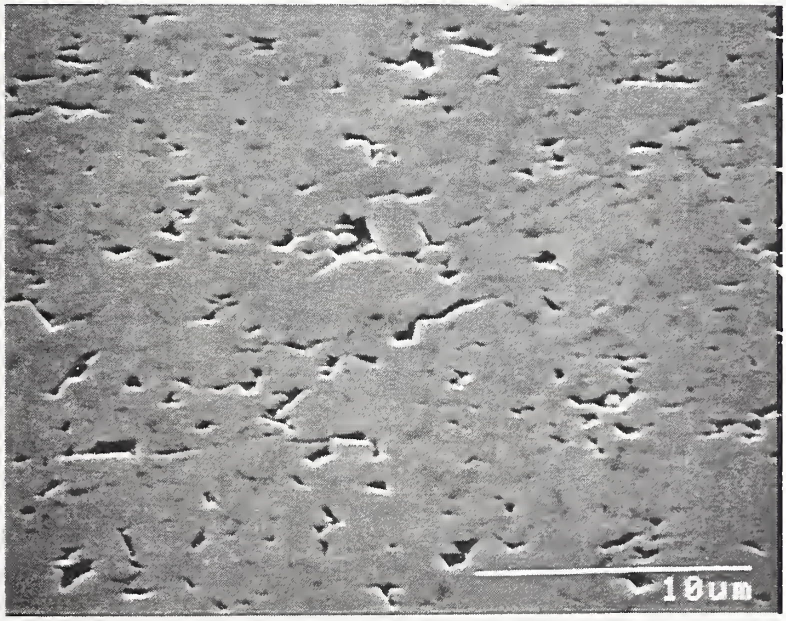


Fig. 37. SEM micrograph of WC-6Co pin surface after wear by 2 μm quartz particles.

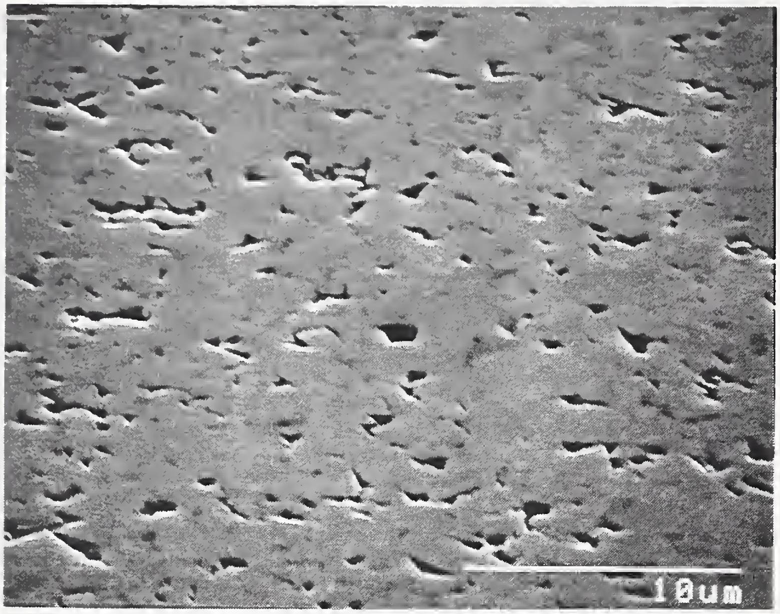


Fig. 38. SEM micrograph of WC-6Co pin surface after wear by 1 μm Al_2O_3 particles.

the 1μm diamond particles. For both quartz and Al_2O_3 particles the otherwise smooth appearing surface contained numerous pits.

Larsen-Basse[39] has considered various wear mechanisms that may occur in the abrasive wear of cemented carbides. With hard abrasives he identifies cutting as the primary mechanism. Grooves are produced by gross deformation and this is accompanied by severe fragmentation of carbide grains and extrusion of binder material. For soft abrasives that do not indent the carbides, he concludes that frictional forces cause the carbide grains to rock back and forth, extruding the binder, which results in the eventual fragmentation or removal of the grains. With very soft abrasives, damage at existing defects (pores or cracks) may occur and the edges of carbide grains may be chipped away leading to rounded or polished appearing grains. Also, soft binder material can be worn from between grains leaving grain edges unsupported and susceptible to fracture. These mechanisms appear to describe the damage shown in Figs. 36-38. The effect of crushing or fragmentation of carbide grains was most evident at the periphery of the wear scar after tests with 3μm Al_2O_3 particles as shown in Fig. 39. It is at the periphery that the abrasive particles are first trapped between the disk and pin surface.

An unexpected outcome of these experiments was the finding that 1μm Al_2O_3 particles and 3μm Al_2O_3 gave similar wear rates.

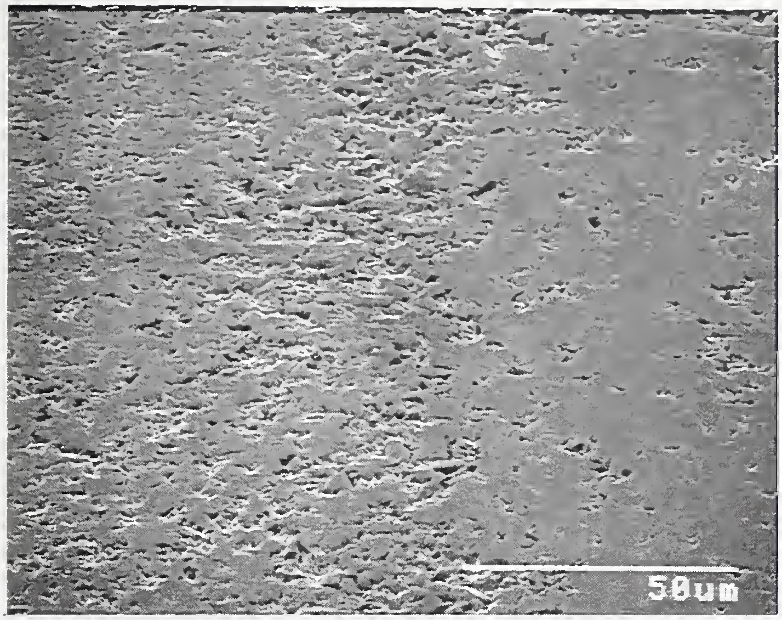


Fig. 39. Edge of wear scar on WC-6Co pin surface after wear by 3 μm Al_2O_3 particles.

However, this may be accounted for by the much higher apparent viscosity of the 1μm particle-oil mixture. As suggested earlier, the increased viscosity associated with large particle concentrations appears to cause an increase in the number of particles entering the contact. This leads to wear rates that are higher than would be expected on the basis of particle concentration effects alone.

5. SUMMARY

The following conclusions are based on results obtained by means of a rotating pin-on-disk test utilizing mineral oil mixed with several different types of particles. Note: conclusions 1 - 9 refer to wear measurements carried out on 52100 steel (bearing ball) pins.

1. Wear rates by raw coal-fuel, coal-fuel combustion particles and mineral matter particles, all derived from the same Kentucky Blue Gem coal, were compared at a concentration of 10%. Relative to mineral oil without added particles, the addition of raw coal-fuel particles led to a 65% increase in wear rate, coal-fuel combustion particles caused a 6-fold increase, and mineral matter particles a 30-fold increase.

2. For coal-fuel combustion, quartz, and Al_2O_3 particles, wear rate increased rapidly at low concentrations, and the harder the particles the more rapid the increase. At intermediate particle concentrations the rate at which wear rate increased was constant and independent of particle hardness. At high particle concentrations where there was a noticeable increase in the viscosity of the oil-particle mixture there was also a significant increase in wear rate with increasing concentration. This was attributed to a greater than proportionate increase in the number of particles entering the contact.

3. The addition of raw coal-fuel particles to mineral oil containing 5% quartz particles led to a marked increase in wear rate when the net particle concentration exceeded ~25%. This effect was attributed to an increase in oil-particle viscosity, as described above.

4. The quantity of oil-particle mixture applied in a test had a significant effect on wear rate. When the quantity of mixture was greater than ~1.5ml, wear rate was not affected. As the quantity was reduced below 1.5ml, wear rate increased reaching a maximum at ~1ml and then decreased. The effect was attributed to the combined influence of fluid flow, film thickness, and the quantity of particles available to enter the contact.

5. Wear rate increased exponentially with an increase in size of quartz particles in the range 1 to 10μm.

6. Wear rate was found to increase exponentially with increasing particle hardness.

7. The antiwear additive zinc dialkyldithiophosphate led to a slight increase in wear rate in tests with abrasive particles.

8. The wear rate with quartz and coal-fuel combustion particles increased significantly when the relative humidity of the surrounding air decreased below 60%. It was hypothesized that at high humidities adsorbed water reduced the fracture strength and corresponding abrasivities of the particles. As the particle concentration was increased above ~20%, relative humidity had little effect.

9. Particle embedment in the 52100 steel disk was observed with Al_2O_3 but not with quartz and coal-related particles.

10. With particles collected from the oil filter of a diesel engine operated on coal-fuel, wear rate was very low ($<60\mu m^3/m$) for materials with hardness greater than about

1000 kg/mm^2 (zirconia, silicon nitride, sapphire, and WC-6Co). Wear rates were about three times higher for the same materials with extracted mineral matter particles.

11. The often observed inverse dependence of wear rate on hardness for ductile materials was not obtained in tests with engine filter particles and extracted mineral matter particles. Nor was an inverse square root dependence obtained for brittle materials with these particles. The observed behavior may be attributed to the range of abrasivities represented by the particle mixtures and to the occurrence of wear modes other than abrasive wear associated with the conditions of the test.

12. The wear rate of cemented carbide, WC-6Co, is strongly dependent on abrasive particle hardness. With quartz particles, which are relatively soft compared to WC-6Co, wear rate is low. Al_2O_3 particles, comparable in hardness to WC-6Co, yield a wear rate that is about three times higher than quartz particles. With diamond particles the wear rate is ten thousand times higher than with either quartz or Al_2O_3 particles.

13. Microcracks, such as those in the vicinity of hardness indentations, lead to increased local damage and enhanced wear during abrasion of brittle materials.

6. RECOMMENDATIONS

The experimental conditions employed in this investigation do not simulate accurately those at the piston ring and cylinder liner contact of an operating coal-fueled diesel engine. Thus, the results can not used to make quantitative projections regarding expected wear performance. Nevertheless, many of the results are sufficiently general in their applicability that the observed trends and relationships should still hold. On this basis, several recommendations can be made regarding the control of wear.

- An effort should be made to maintain the concentration of hard particles, particularly quartz and hard silicates, at as low a level as possible, and not just the overall concentration of mineral matter in coal. Certainly, the presence of such very hard particles as aluminum oxide should be avoided.

- Conditions that lead to high concentrations of particles are likely to lead to high wear rates. However, it is the number of particles that actually enter the contact that is important. Considerable benefit could be obtained from design approaches that limit entry of particles into the contact between the piston ring and cylinder wall.

- Particle size should be kept as small as possible. Large particles lead to substantially higher wear rates than small particles, at least to the extent that large particles are able to enter the contact.

- The piston ring and cylinder liner surfaces should be appreciably harder than quartz if satisfactory wear life is to be achieved. However, toughness is also an important property. Even in the absence of substantial abrasion, the presence of microcracks (introduced during grinding, for example) and other flaws in brittle materials can lead to severe surface damage.

7. ACKNOWLEDGEMENTS

I wish to express my appreciation and thanks to the following for providing various particulate materials used in the experiments: R. L. Mehan, A. W. Giammarise, and C. L. Spiro of General Electric Company; R. M. Kakwani and P. R. Badgley of Adiabatics, Inc.; and D. S. Keller of Otisca Industries, Ltd.

8. REFERENCES

1. H. Wahl, The Limits of the Coal Dust Engine, ERDA-TR-180, p. 46. (translation of Die Grenzen des Kohlenstaubmotors, Technischer Verlag der Buch- und Tiefdruck Gesellschaft mbH, Berlin, 1940).

2. S. E. Nydick, F. Porchet and H. A. Steiger, "Continued Development of a Coal/Water Slurry-Fired Slow-Speed Diesel Engine: a Review of Recent Test Results," ASME Journal of Engineering for Gas Turbines and Power, 109 1987, pp.465-476.

3. P. L. Flynn, G. L. Leonard and R. L. Mehan, "Component Wear in Coal-Fueled Diesel Engines," ASME Journal of Engineering for Gas Turbines and Power 111 1989, pp. 521-529.

4. A. K. Rao, R. P. Wilson, E. N. Balles, R. A. Mayville, M. H. McMillian, and J. A. Kimberley, "Cooper-Bessemer Coal-Fueled Engine System——Progress Report," ASME Journal of Engineering for Gas Turbines and Power 111 1989, pp. 498-506.

5. R. A. Mayville, A. K. Rao and R. P. Wilson, "Cooper-Bessemer Coal-Fueled Engine System: Recent Developments in Durable Components," in Coal-Fueled Diesel Engines 1990, ICE-Vol. 12, J. A. Caton, Ed., ASME, New York, NY, 1990, pp. 17-22.

6. L. K. Ives, M. B. Peterson and E. P. Whitenton, "Mechanisms of Galling and Abrasive Wear," in AR&TD Fossil Energy Materials

Program Semiannual Progress Report for the Period Ending September 30, 1988, ONRL/FMP-88/2, Oak Ridge National Laboratory, Oak Ridge, TN, January 1989, pp. 445-462.

7. L. K. Ives, M. B. Peterson and E. P. Whitenton, "Mechanisms of Galling and Abrasive Wear," in AR&TD Fossil Energy Materials Program Semiannual Progress Report for the Period Ending March 31, 1989, ONRL/FMP-89/1, Oak Ridge National Laboratory, Oak Ridge, TN, July, 1989, pp. 455-469.

8. L. K. Ives, M. B. Peterson and E. P. Whitenton, "Mechanisms of Galling and Abrasive Wear," in Fossil Energy Advanced Research and Technology Development Materials Program Semiannual Progress Report for the Period Ending September 30, 1989, ONRL/FMP-89/2, Oak Ridge National Laboratory, Oak Ridge, TN, January, 1990, pp. 447-465.

9. L. K. Ives, M. B. Peterson and E. P. Whitenton, "Mechanisms of Galling and Abrasive Wear," in Proceedings of the Fourth Annual Conference on Fossil Energy Materials, Oak Ridge National Laboratory, Oak Ridge, TN, August 1990, Conf. 900546, ONRL/FMP-90/1, pp. 417-426.

10. L. K. Ives, "Mechanisms of Galling and Abrasive Wear," in Fossil Energy Advanced Research and Technology Development Materials Program Semiannual Progress Report for the Period Ending September 30, 1990, ONRL/FMP-90/2, Oak Ridge National Laboratory, Oak Ridge, TN, December 1990, pp. 341-352.

11. L. K. Ives, "Wear by Coal-Fueled Diesel Engine Particles," in Proceedings of the Fifth Annual Conference on Fossil Energy Materials, Oak Ridge, TN September 1991, Conf. 9105184, ORNL/FMP-91/1, pp. 367-376.

12. L. K. Ives, "Abrasive Wear by Coal-Fueled Engine Particles," Proceedings Corrosion-Erosion-Wear of Materials at Elevated Temperatures, A. V. Levy, ed., NACE, Houston, TX, 1991, pp. 29-1 thru 29-20.

13. J. A. Schwalb, T. W. Ryan III, and W. C. Smith, "Lube Oil Contamination Induced Wear in Coal-Fueled Diesel Engines," in Coal-Fueled Diesel Engines 1990, ICE-Vol. 12, ASME, New York, NY, 1990, pp. 51-58.

14. R. M. Kakwani, P. R. Badgley and W. C. Smith, "Development of Fuel Injection and Combustion Systems for Coal-Water-Slurry Fueled Diesel Engines," in Coal-Fueled Diesel Engines 1990, ICE-Vol. 12, J. A. Caton, Ed., ASME, New York, NY, 1990, pp. 41-50.

15. "Test Method for Wear Testing with a Pin-On-Disk Apparatus," G99-90, 1991 Annual Book of Standards, Vol. 03.02, ASTM, Philadelphia, PA, 1991, pp. 387-391.

16. L. K. Ives and M. B. Peterson "Effect of Solid Additives on Wear by Greases Containing Abrasive Particles," Wear of Materials - 1985, K. C. Ludema, ed., ASME, NY, 1985, pp. 355-363.

17. J. K. Lancaster, "An Apparatus for Measuring Small Amounts of Abrasion by Finely Divided Solids," Tribology International 1 1968, pp. 240-243.

18. F. J. Simmons and D. V. Keller, Jr., "Two Ton-Per-Day Production of Otisca T-Process Ultra-Clean Coal/Water Slurry," 10th International Coal Preparation Congress, September 1-5, 1986, Edmonton, Canada.

19. R. C. Streeter, "Evaluation of the Effect of Coal Cleaning on Fugitive Elements—Phase IV Identification of Mineral Forms in Coal," BCR Report L-1551, (1986), Available from NTIS Springfield, VA.

20. R. D. Harvey and R. R. Ruch, "Mineral Matter in Illinois and Other U.S. Coals," in Mineral Matter and Ash in Coal, K. S. Vorres, Ed., American Chemical Society, Washington, D.C., 1986, pp. 10-40.

21. D. V. Keller, Jr., "Separation of Mineral Matter from Pittsburgh Coal by Wet Milling," in Mineral Matter and Ash in Coal, K. S. Vorres, Ed., American Chemical Society, Washington, D.C., 1986, pp. 473-484.

22. P. J. Shields, C. L. Spiro and E. F. Koch, "Phase Characterization of Coal-Fueled Turbine Deposits," in Fly Ash and Coal Conversion By-Products: Characterization, Utilization and Disposal IV, G. J. McCarthy, F. P. Glasser, D. M. Roy, and R. T. Hemmings, Mat. Res. Soc. Symp. Proc. Vol. 113, Materials Research Society, Pittsburgh, PA 1988, pp. 133-142.

23. R. M. Kakwani, R. Kamo, R. G. Cutlip, and W. C. Smith, "Combustion Characteristics of Dry-Coal-Powder-Fueled Adiabatic Diesel Engine, Coal-Fueled Diesel Engines, ICE-Vol. 7, ASME, New York, NY, 1989, pp. 27-34.

24. B. D. Hsu, "Progress on the Investigation of Coal-Water Slurry Fuel Combustion in a Medium Speed Diesel Engine: Part 1 - Ignition Studies," Journal of Engineering for Gas Turbines and Power, 110, 1988, pp. 415-422.

25. H. Heshmat, "Powder-Lubricated Piston Ring Development," MTI 91TR14 Mechanical Technology Inc., Latham, NY, 1991 (Available from NTIS Springfield, VA).

26. G. P. Tilly, "Erosion Caused by Airborne Particles," Wear 14, 1969, pp. 63-79.

27. M. H. McMillian and H. A. Webb, "Coal-Fueled Diesels: Systems Development," Journal of Engineering for Gas Turbines and Power, 111, 1989, pp. 485-490.

28. M. M. Khruschov, "Principles of Abrasive Wear," Wear 28 (1974) pp. 69-88.

29. R. C. D. Richardson, "The Wear of Metals by Relatively Soft Abrasives," Wear 11 (1968) pp. 245-275.

30. A. Misra and I. Finnie, "An Experimental Study of Three-Body Abrasive Wear," Wear of Materials - 1981, S. K. Rhee, A. W. Ruff and K. C. Ludema, eds., ASME, NY (1981) pp. 426-431.

31. J. L. Xuan, I. T. Hong and E. C. Fitch, "Hardness Effect on Three-Body Abrasive Wear Under Fluid Film Lubrication," ASME Journal of Tribology 111 (1989) pp. 35-40.

32. F. Hirano and S. Yamamoto, "Four-Ball Test on Lubricating Oils Containing Solid Particles," Wear 2 (1958/59) pp. 349-363.

33. J. Larsen-Basse, "Influence of Atmospheric Humidity on Abrasive Wear—I. 3-Body Abrasion," Wear 31 (1975) p. 373-379.

34. S. Malkin, Grinding Technology, Ellis Horwood, Ltd., 1989, p. 213.

35. A. G. Evans and D. B. Marshall, "Wear Mechanisms in Ceramics," in Fundamentals of Friction and Wear of Materials, D. A. Rigney, ed., ASM, Metals Park, OH (1981) pp. 439-452.

36. T. E. Fischer, "Friction and Wear of Ceramics," Scripta Met. 24 (1990) pp. 833-838.

37. M. M. Khruschov, "Principles of Abrasive Wear," Wear 28 (1974) pp. 69-88.

38. A. Misra and I. Finnie, "An Experimental Study of Three-Body Abrasive Wear," Wear of Materials - 1981, S. K. Rhee, A. W. Ruff and K. C. Ludema, eds., ASME, NY (1981) pp. 426-431.

37. J. G. Baldoni, S. F. Wayne and S. T. Buljan, "Cutting Tool Materials: Mechanical Properties—Wear-Resistance Relationships," ASLE Transactions 29 (1986) pp. 347-352.

38. S. F. Wayne, J. G. Baldoni and S.-T. Buljan, "Abrasion and Erosion of WC-Co With Controlled Microstructures," Tribology Transactions 33 (1990) pp. 611-617.

39. J. Larsen-Basse, "Resistance of Cemented Carbides to Sliding Abrasion: Role of Binder Metal," Science of Hard Materials, R. K. Viswanadham, D. J. Rowcliffe, and J. Gurland, eds. Plenum Press, NY, 1981, pp. 797-813.

DISTRIBUTION

AIR PRODUCTS AND CHEMICALS
P.O. Box 538
Allentown, PA 18105
S. W. Dean
S. C. Weiner

ARGONNE NATIONAL LABORATORY
9700 S. Cass Avenue
Argonne, IL 60439
W. A. Ellingson
K. Natesan

AVCO RESEARCH LABORATORY
2385 Revere Beach Parkway
Everett, MA 02149
R. J. Pollina

BABCOCK & WILCOX
1562 Beeson St.
Alliance, OH 44601
T. I. Johnson
T. Modrak

BABCOCK & WILCOX
Domestic Fossil Operations
20 South Van Buren Avenue,
Barberton, OH 44023
M. Gold

BABCOCK & WILCOX
Lynchburg Research Center
P.O. Box 11165
Lynchburg, VA 24506
H. Moeller

BATTELLE-COLUMBUS LABORATORIES
505 King Avenue
Columbus, OH 43201
I. G. Wright

BRITISH COAL CORPORATION
Coal Research Establishment
Stoke Orchard, Cheltenham
Glochester, England GL52 4RZ
M. Arnold
C. Bower
A. Twigg

BRITISH GAS CORPORATION
Westfield Development Centre
Cardenden, Fife,
Scotland KY5OHP
J. E. Scott

BROOKHAVEN NATIONAL LABORATORY
Department of Applied Science,
Upton, Long Island, NY 11973
T. E. O'Hare

CANADA CENTER FOR MINERAL & ENERGY TECHNOLOGY
568 Booth Street
Ottawa, Ontario
Canada K1A OG1
R. Winston Revie
Mahi Sahoo

COMBUSTION ENGINEERING
1000 Prospect Hill Road
Windsor, CT 06095
D. A. Canonico

CONSOLIDATION COAL COMPANY
4000 Brownsville Road
Library, PA 15129
S. Harding

ELECTRIC POWER RESEARCH INSTITUTE
P.O. Box 10412
3412 Hillview Avenue
Palo Alto, CA 94303
W. T. Bakker
J. Stringer

EUROPEAN COMMUNITIES JOINT RESEARCH CENTRE
Petten Establishment
P.O. Box 2
1755 ZG Petten
The Netherlands
M. Van de Voorde

FLUIDIZED BED TECHNOLOGIES
P. O. Box 4469
Chattanooga, TN 37405
R. Q. Vincent

FOSTER WHEELER DEVELOPMENT CORPORATION
Materials Technology Department
John Blizard Research Center
12 Peach Tree Hill Road
Livingston, NJ 07039
J. L. Blough

GAS RESEARCH INSTITUTE
8600 West Bryn Mawr Avenue
Chicago, IL 60631
H. S. Meyer

GENERAL ELECTRIC COMPANY
1 River Road,Bldg. 55, Room 115
Schenectady, NY 12345
R. W. Haskell

LAWRENCE BERKELEY LABORATORY
University of California
Berkeley, CA 94720
A. V. Levy

LAWRENCE LIVERMORE LABORATORY
P.O. Box 808, L-325
Livermore, CA 94550
W. A. Steele

MOBIL RESEARCH & DEVELOPMENT CORPORATION
P. O. Box 1026
Princeton, NJ 08540
R. C. Searles

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Materials Building
Gaithersburg, MD 20899
L. K. Ives

NATIONAL MATERIALS ADVISORY BOARD
National Research Council
2101 Constitution Avenue
Washington, DC 20418
K. M. Zwilsky

NEW ENERGY AND INDUSTRIAL TECHNOLOGY DEVELOPMENT ORGANIZATION
Sunshine 60 Bldg.
P.O. Box 1151
1-1, Higashi-Ikebukuro 3-chrome
Toshima-Ku
Tokyo, 170
Japan
H. Narita
S. Ueda

OAK RIDGE NATIONAL LABORATORY
P.O. Box 2008
Oak Ridge, TN 37831
P. J. Blau
P. T. Carlson
N. C. Cole
R. R. Judkins
J. R. Keiser
R. A. Lawson (8 copies)

RISOE NATIONAL LABORATORY
P.O. Box 49
DK-4000, Roskilde
Denmark
Aksel Olsen

SHELL DEVELOPMENT COMPANY
P. O. Box 1380
Houston, TX 77251-1380
L. W. R. Dicks

TENNESSEE VALLEY AUTHORITY
Energy Demonstration & Technology
MR 2N58A
Chattanooga, TN 37402-2801
C. M. Huang

TENNESSEE VALLEY AUTHORITY
1101 Market Street
3A Missionary Ridge
Chattanooga, TN 37402-2801
A. M. Manaker

UNIVERSITY OF CALIFORNIA AT BERKELEY
Department of Mechanical Engineering
Berkeley. CA 94720
J. A. C. Humphrey

UNIVERSITY OF NOTRE DAME
Department of Materials Science and Engineering
P.O. Box E
Notre Dame. IN 46556
T. H. Kosel

WESTERN RESEARCH INSTITUTE
365 N. 9th Street
P.O. Box 3395
University Station
Laramie, WY 82071
V. K. Sethi

WESTINGHOUSE ELECTRIC CORPORATION
Research and Development Center
1310 Beulah Road
Pittsburgh. PA 15235
S. C. Singhal

WESTINGHOUSE HANFORD COMPANY
P.O. Box 1970
W/A-65
Richland. WA 99352
R. N. Johnson

DOE
DOE OAK RIDGE FIELD OFFICE
P. O. Box 2001
Oak Ridge, TN 37831
Assistant Manager for Energy Research and Development

DOE
DOE OAK RIDGE FIELD OFFICE
P. O. Box 2008
Building 4500N, MS 6269
Oak Ridge, TN 37831
E. E. Hoffman

DOE
OFFICE OF BASIC ENERGY SCIENCES
Materials Sciences Division
ER-131, GTN
Washington, DC 20545
J. B. Darby

DOE
OFFICE OF FOSSIL ENERGY
Washington, DC 20545
J. P. Carr (FE-14) GTN

DOE
MORGANTOWN ENERGY TECHNOLOGY CENTER
P.O. Box 880
Morgantown, WV 26505
R. A. Bajura
R. C. Bedick
D. C. Cicero
F. W. Crouse, Jr.
N. T. Holcombe
W. J. Huber
M. J. Mayfield
J. E. Notestein
J. S. Wilson

DOE
PITTSBURGH ENERGY TECHNOLOGY CENTER
P.O. Box 10940
Pittsburgh, PA 15236
A. H. Baldwin
G. V. McGurl
R. Santore
T. M. Torkos

NIST-114A (REV. 3-90)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 4811

2. PERFORMING ORGANIZATION REPORT NUMBER
SEPTEMBER 1992

3. PUBLICATION DATE

4. TITLE AND SUBTITLE

Abrasive Wear by Coal-Fueled Diesel Engine and Related Particles

5. AUTHOR(S)

L K Ives

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

U S Department of Energy
Advanced Research and Technology Development
Fossil Energy Materials Program
Washington, DC

10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

The development of commercially viable diesel engines that operate directly on pulverized coal-fuels will require solution to the problem of severe abrasive wear. The purpose of the work described in this report was to investigate the nature of the abrasive wear problem. Analytical studies were carried out to determine the characteristics of the coal-fuel and combusted coal-fuel particles responsible for abrasion. Laboratory pin-on-disk wear tests were conducted on oil-particle mixtures to determine the relationship between wear rate and a number of different particle characteristics, contact parameters, specimen materials properties, and other important variables.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

abrasion; abrasive wear; coal; coal-fuel; diesel engine wear; exhaust particles; 52100 steel; lubrication; pin-on-disk test; relative humidity; wear

13. AVAILABILITY

- [X] UNLIMITED
- [ ] FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).
- [ ] ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
- [X] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES

67

15. PRICE

A04

ELECTRONIC FORM